CLIMATE CHANGE, ASYMMETRIC COSTS, AND THE CHALLENGE TO THE CAPITALIST SYSTEM OF PRODUCTION: A MACROECONOMIC PERSPECTIVE

by

Jason Matthew Whittle

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STATEMENT OF DISSERTATION APPROVAL

The dissertation of **Jason Matthew Whittle**

has been approved by the following supervisory committee members:

Korkut Alp Ertürk	, Chair	**5/19/2015** Date Approved
Rudiger von Arnim	, Member	**5/29/2015** Date Approved
Richard Fowles	, Member	**5/1/2015** Date Approved
Minqi Li	, Member	**5/1/2015** Date Approved
Brett Clark	, Member	**5/1/2015** Date Approved

and by **Thomas Maloney** , Chair/Dean of

the Department/College/School of **Economics**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

This dissertation consists of three papers, each of which addresses what I believe are important gaps in the literature. The first is the impact regional asymmetric costs can have on mitigation and adaptation decisions. Regional cost asymmetries are not unknown in the extant literature, but their implications are generally ignored in much of the modeling that exists. The second gap involves the cursory treatment climate science findings receive in macroeconomic modeling. Development of climate system dynamics from climate science has continued over the last two decades, but little progress has been made on incorporating new developments into post-Keynesian macromodels. Finally, the third gap is the lack of time series methods in the empirical research on the climate-macroeconomic interaction from a global perspective. It is known that GDP (Gross Domestic Product) and CO_2 production are highly related, but questions remain as to how this relation works and whether it is changing over time.

To my partner, mother, and best friends: Tawny L. Burton, Vilate Whittle, Jo, Koda, and Mud.

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CHAPTER 1

CLIMATE CHANGE, PROCRASTINATION, AND ASYMMETRIC POWER

Korkut Alp Ertürk and Jason Whittle[1]

This paper argues that policy conclusions of the economics of climate change literature based on 'integrated assessment models' (IAM) fail to take into account the intricacies of collective action. Specifically, IAMs do not account for how asymmetric power between developed and undeveloped countries changes the former's payoff matrix with respect to mitigation and adaptation strategies. Using a simple one-sided prisoner's dilemma model, the paper illustrates how developed countries' power to externalize their emissions to the global commons skews their cost-benefit calculation in favor of putting off mitigation efforts into the future. Undeveloped countries, on the other hand, are incentivized to act in concert to deter developed countries from passing their climate costs onto them in the present. The extent to which they may succeed in doing so also helps developed countries overcome their 'short-termism' on climate change policy.

[1] We would like to thank Richard Pereira, John Tomer, Tarik Banuri, Hans Ehrbar, and Brett Clark for all their helpful comments and acknowledge full responsibility for all the errors that remain.

1.1. Introduction

The current ongoing debate on what to do about anthropogenic climate change boils down to two essential options, *mitigation* or *adaptation*. Mitigation involves an attempt to avoid climate change all together by limiting greenhouse gas (GHG) output now. Adaptation involves putting off dealing with the impacts of climate change into the future. Adaptation is a strategy of incurring costs in the long term whereas mitigation is a strategy of incurring them much sooner.

A curious divergence of opinion has developed between climatologists and economists on the preferred course of action with respect to these two policy options in recent years. The weight of opinion among the former has decisively shifted towards mitigation, but economists have continued to favor adaptation, arguing that the costs of trying to mitigate climate change right away might exceed its benefits.

Economists' arguments derive from cost-benefit analyses based on models that specify what policy is optimal. These models are often criticized for the unreliability of their assumptions, for understating costs and the risk of adverse climatic responses to warming while being overly sanguine about the ability of human societies to adapt to future impacts of climate change. More importantly, they are also criticized for ignoring the uncertainty about the possibility of an ecological catastrophe, the risk of which increasingly worries climatologists. Although we agree with these criticisms and point to the conceptual limitations of the type of cost-benefit analyses they undertake as others have done (Akerman, DeCanio, Howarth, & Sheeran, 2009; Ackerman & Stanton, 2013; Pindyck, 2013; Stern, 2007; Tol, Frankhauser, Kuik, & Smith, 2003,), our criticism takes a rather different tack. We argue that economists' models and policy conclusions ignore the intricacies of collective action. Perfunctory references to the 'tragedy of the commons' and the 'free-riding problem' are commonplace in this literature, but there is little recognition of how costs distributed across agents with asymmetric power can distort cost-benefit calculus and change what policy option is 'optimal'. In addition to having important policy implications, this lack of recognition also matters for the discourse on climate change policy, since economists often make the heroic assumption that societies, just like individuals, would do what is optimal if they are 'rational.'

Most studies consider whether or not a strategy of mitigation or adaptation is in the best interest of an individual country or a group of countries in a region. Whether or not collective action is achieved in favor of pursuing a global policy of mitigation depends on a critical mass of countries or regions finding such a policy to have a clear cost-benefit interest for them individually. Often, this is where the analysis ends. Of course, however, what policy is optimal for an individual country depends very much on what others do, and thus the argument becomes circular when we try to determine the collective outcome by summing up individual decisions.

Adaptation involves the emitter distributing its GHG emissions into the global commons, externalizing them into all countries and regions regardless of their own emissions and level of vulnerability. Mitigation, by contrast, entails the emitter internalizing the costs it emits within its economy. Two general implications follow from this. One, because costs of mitigation are incurred individually whereas its benefits accrue to all, adaptation gives its pursuers a free-ride by those who mitigate. Given this intrinsic free-rider problem, mitigation requires extensive if not full cooperation and is thus hard to achieve, making adaptation the default outcome. Two, mutual defection from cooperation, i.e., all around adaptation that involves distributing costs to the global commons by all, amounts to passing on costs from high to low emitters.

Given the strong correlation between the rate of emission and the level of economic activity, low emitters are generally the poor and high emitters the rich countries. Poor countries also tend to be located in regions more vulnerable to climate change, which also lowers their bargaining power over global policy on climate change. Asymmetric power between the rich and the poor enables high emitters to shift costs onto the low emitters with relative impunity, and that makes "kicking the can down the road" tempting for developed countries, undercutting their interest in forging the harder to achieve but in the long run the superior, coordinated solution mitigation requires. Procrastination, however, could lose much of its appeal if the emitters lacked the power to pass on costs with impunity. If all adversely affected powerless actors could act in unison to deter cost shifting by the emitters, mitigation might become the preferred policy for the powerful players. In other words, the power balancing effect of such a coalition could be the very impetus for overcoming short-termism and instead acting in their long-term enlightened self-interest, which implies that in evaluating different policy options, an important consideration should be whether they help or hinder coalition building on the part of the powerless actors.

The rest of the paper is organized as follows. In subsections 2.1 and 2.2, we give a brief overview of the positions taken, respectively, by economists and climatologists on climate change. In subsections 2.3 and 2.4, we situate the climate change policy debate in the context of a clash between short-term and long-term objectives and go on to argue in subsection 2.5 the link between asymmetric power and short-termism on the part of developed countries. We emphasize the importance of power balancing by undeveloped countries through coalition building in overcoming 'short-termism' and point to the policy implications of our argument. We end with a brief conclusion.

1.2. The Economics of Climate Change

Economic studies of climate change impact began in the late 1980s and early 1990s (Cline, 1992; Nordhaus, 1991, 1992). Many of these studies looked at a single country such as the U.S., asking what the impact would be of a doubling of the preindustrial level of atmospheric CO_2 concentration (560 ppm) on sectors of the economy most dependent on nature such as agriculture. Since agriculture makes up only about 2 to 3% of the U.S. and most other OECD countries' GDP (Tol et al., 2003) and other vulnerable sectors make a similarly small relative contribution, these initial estimates of the economic impact of global warming were small. When these country-specific studies were aggregated to the rest of the world, the global impact was likewise found to be relatively insignificant.[2] This first generation of impact assessment models estimated about a 1.5 to 2% cost in terms of global GDP for a doubling of pre-industrial CO2 concentration with associated levels of warming in the range of 2.5c (Tol et al., 2003).[3] Clearly, none of these studies lent support to a policy of mitigation as they seemed to suggest that waiting to mitigate greenhouse gas emissions (implicitly choosing an adaptation policy) involved relatively modest costs.

[2] See, for instance, Nordhaus' (1992) DICE model.
[3] In these models, the warming levels assumed from given increases in CO_2 concentration are rather optimistic in comparison to the IPCC (2007) estimates.

However, most developing countries derive a much higher relative share of their GDP from agriculture, often in excess of 50%, than do OECD countries, and thus using the U.S. or Europe's agricultural impact as a baseline for these countries grossly underestimated the impact of climate change on developing countries (Nordhaus & Yang 1996; Tol et al., 2003). The problem was addressed by regionally calibrating the impact assessment models (Mendelsohn, Dinar, & Williams, 2006; Mendelsohn & Schlesinger, 1999; Nordhaus & Yang, 1996). These so-called 'integrated assessment models' (IAMs) showed that different regions in the world would be affected very differently by climate change, especially in the initial phase of global warming. Out of this literature came the 'hill-shaped' response function to climate change (Mendelsohn et al., 2006). According to this function, the impact of rising temperature is initially positive on a *cool* region's economy and becomes negative only past a certain threshold after the region's climate becomes too warm. The regions that are already warm in lower latitudes in many parts of Africa and Southeast Asia with limited ability to protect coastal areas are the most vulnerable (Mendelsohn et al., 2006). By contrast, warming initially is expected to move other regions such as Russia, Canada, some parts of the U.S., and Europe, to a temperature level that might be economically beneficial (Mendelsohn et al., 2006).

These findings implied that developed regions had less of an incentive to opt for corrective action early on than undeveloped and regionally vulnerable areas. The latter faced not only immediate costs but also the prospect that these costs could accumulate to debilitating and possibly catastrophic levels by the time developed countries ceased externalizing costs to the commons. Yet, factoring in undeveloped countries' losses did not tip the scales much in a global cost-benefit analysis,[4] because relatively small gains in a country like the U.S. more than offset the economic devastation in smaller undeveloped countries in the aggregate because of the smaller size of their economies.[5] Thus, delaying mitigation could be shown to involve a net benefit until warming reached higher levels, which led to the notion that there was some 'optimal' level of warming.

Nordhaus (2010) specifies what this optimal level might be and compares it against several different climate scenarios. He starts out by calibrating a worst-case baseline scenario, involving a situation where no action is taken by world governments with emission growth proceeding unchecked. Atmospheric CO_2 concentrations reach 795 ppm by 2100 and top 1200 ppm by 2200. Warming from such levels of CO_2 is estimated to reach 3.5c by 2100, eventually peaking at a 6.7c increase relative to 1900 temperatures. It is uniformly accepted that such levels of warming would most likely involve an ecological disaster (IPCC, Core Writing Team, 2007).

Nordhaus' 'optimal' scenario, an example of what an 'adaptation' strategy might look like, involves the reduction of CO_2 emission level to 50% of its 2005 level by 2100, where warming peaks at a 3c increase with atmospheric concentration rising to 600 ppm.[6]

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[4] Note that these models made the implicit assumption that the marginal utility of consumption in poor countries is the same as that in rich countries. Known as 'Negishi-weighing,' this assumption basically amounts to ruling out of consideration any improvement in global welfare through income redistribution (Stanton, 2009). We thank Tariq Banuri for pointing this out.

[5] These estimates from the 1990s predate the explosive economic growth of China and India. In Nordhaus and Yang (1996), India is part of "the rest of the world" but China is mentioned only in passing. Today, China is the second largest national economy and the largest emitter of CO_2 in the world. Reaching any global climate targets today would require both China and India to mitigate along with developed countries.

[6] These estimates are again on the optimistic side of the spectrum as they leave out land use changes and greenhouse gases other than CO_2, and assume the lower bound of probable warming from a 600 ppm concentration. IPCC, Core Writing Team (2007, p.

Comparing the optimal with the baseline scenario, he estimates that the former yields a higher level of global consumption by 8.06 trillion in 2005 USD, a 0.35% improvement in discounted income over the baseline scenario. He then compares the optimal (adaptation) scenario with what might be called mitigation, defined as maintaining a 2c ceiling on warming by taking more immediate action, which the climate science community has been advocating (more on this below). He calls this the 'temperature limited' case and estimates that it requires again roughly a 50% cut in emissions from their 2005 levels, but much sooner, by 2075. Now, CO_2 concentration rises to 500 ppm by mid-century and eventually stabilizes at 450 ppm. This case also fares significantly better than the worst-case baseline scenario, yielding a 4.37 trillion dollar higher discounted income, a 0.19% increase in discounted income, but falls short of the optimal case by roughly half.

This is perhaps the clearest statement of the basis on which economists believe that developed countries can reap a net benefit from delaying mitigation. They oppose trying to limit warming to 2c or less, since that becomes very costly "because of the difficulty of attaining that target with so much inertia in the climate system" (Nordhaus, 2010, p. 11724). The intriguing question is whether economists might be peddling fool's gold. At the risk of sounding alarmist, climatologists think that delaying mitigation is tantamount to playing Russian roulette with the planet's very survival. For them, the notion that one part of the planet can benefit from warming while the other part is devastated is not only misguided but also a dangerous illusion (Stern, 2007).

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66) estimates that warming from the same level of CO_2 concentration (600ppm) can be as high as 6c.

1.3. Climatologists

When looked at from the point of view of climate science, the picture is grim. Climate scientists warn that humanity is risking leaving behind the very climatological epoch - the Holocene era of the last 12,000 years - that gave it agriculture, science, and industry (Hansen et al., 2008). Their main concern is that warming can trigger a nonlinear reaction that takes the planet to a fundamentally different climate system where warming intensifies independently of what humans do. If that were to happen, any mitigation effort at that point would be too late.

With global temperature at its warmest level in the Holocene, little additional climate forcing from GHG emissions and land use changes is required to trigger positive feedbacks. Rapid melting of land ice as recently observed in Greenland[7] is an example of the kinds of changes that can give rise to the feared positive feedback effects given that ice reflects 90% of the solar radiation hitting it whereas water and land absorb nearly all of it. The rising CO_2 content of the deep oceans and surface albedo can also trigger positive feedback effects. If these changes show up earlier than expected, as is now more likely than before, warming can proceed even without any additional forcing. Climate change would then be locked into a trajectory of automatic warming that could be next to impossible to mitigate, which is what climatologists are becoming increasingly concerned about (Hansen, 2008; IPCC, Core Writing Team, 2007, 2014; Stern, 2007).

No one knows with any precision when such a tipping point might occur. Yet, there is little doubt that these tipping points are real, and that makes the situation alarming. In previous periods of higher CO_2 ppm atmospheric concentrations and higher

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[7] In the summer of 2012, the melting in the Greenland ice sheet in just 4 days jumped from 40% to 97%: http://www.nasa.gov/topics/earth/features/greenland-melt.html.

temperature, the speed at which CO_2 ppm increased was approximately 0.01 ppm per year. Now, humans are increasing it by 2 ppm per year (Hansen, Caldeira, & Rohling, 2011). Never before in Earth's recorded history has so much CO_2 been added to the atmosphere from year to year. It is possible that warming up to the economically 'optimal' level of 3c might entail crossing some tipping points. Of course, building in additional warming beyond 3c will only increase the risk of passing that critical threshold beyond which mitigation becomes much more costly, if at all possible.

Because crossing tipping points can have such grave consequences, climatologists call for immediate action to prevent them from happening at all costs (Hansen, 2008; Hansen et al., 2008; Hansen et al., 2011; IPCC, Core Writing Team, 2007, 2014; Stern, 2007). In their view, the current CO_2 ppm concentration of 400 ppm is already too high. Even if such tipping points are not crossed, warming risks causing irreparable damage to the ecosystem as it is. The northerly migration of plant and animal zones that has already been taking place is an alarming sign. Given that humanity relies on the ecosystem for its survival, pushing it to its breaking point threatens not only polar bears but also civilization itself (Hansen, 2008).[8] Minimizing the risk we face requires that climate change be limited to 2c, and that means the CO_2 concentration should not be allowed to exceed 350 ppm. Thus, staying in the "safe" range requires immediate action, which the most recent 2014 IPCC again calls for with even more dire warnings than in 2007.

However, although there might be little uncertainty that climate change is happening, climate science still lacks precision on many questions: how much and how

[8] As Daly (1997) and other ecological economists have argued for a long time, it is important not to lose sight of the fact that the economic system resides within the larger ecosystem.

fast warming will occur; how sensitive the climate will be to rising CO_2 levels, land use changes, and other greenhouse gases; and how the Earth will change climatically and physically at rising levels of warming. Thus, cost estimates unsurprisingly remain far from robust and fail to converge over time. In fact, the danger of an ecological disaster and the uncertainty it creates brings into question the very viability of the exercise. If future contingent outcomes cannot even be specified given the level of uncertainty, cost estimates end up becoming arbitrary as slight variations in what contingent scenarios unfold produce drastically different results.[9] How does one quantify the increased extinction risk of a given percentage of species and estimate its implications for the ecosystem over time?

1.4. Changing Preferences and Procrastination

Economists engage in considerable cherry picking in their cost benefit analyses, but otherwise, their assumptions are based on climate science, albeit with a time lag. As climate scientists' forecasts become more pessimistic over time, economists are soon likely to revise their optimistic assumptions at least on issues related to hard science. One exception that appears impervious to changing opinion within climate science involves *discounting*, a putative forte of economists.

With a given set of science-based assumptions, the balance between the present value of long-run costs and benefits from growth can vary drastically depending on what

[9] Most economics models neglect possible sudden impacts such as rapid ice melt off or sudden sea level rise let alone an ecological catastrophe, however defined (Akerman et al., 2009; Pindyck, 2013; Roughgarden & Schneider, 1999; Stern, 2007). See Weitzman (2011) for a broader discussion of deep structural uncertainty and "fat tails" in critical probability distributions in climate change research.

discount rate one uses.[10] Economists postulate a *pure* discount rate based on the presumption that a time-invariant time preference of consumption exists for humanity as a whole.[11] This rate supposedly captures our inborn impatience, which makes us prefer consumption today over consumption tomorrow. A higher discount rate values current consumption more heavily relative to future consumption in general and, holding all else constant, makes mitigation less desirable given that future costs then weigh relatively less today.

We believe that economists can make a better contribution to the debate on climate change if they focus on how behavior might be affected when preferences evolve over time rather than postulating an invariant discount rate that seems unconvincing. Defining our relative preference for immediate consumption independently of what we think of how our actions today might influence the future might be of doubtful value. Given that our preferences are all mediated by some form of cognition[12] (Bowles, 1998), it is only reasonable to think that they would change when our understanding of how what we do today affects what happens in the future changes. Thus, as humanity absorbs the findings of climate science regarding the risks associated with delayed action on climate change, the notion that the *pure* discount rate would militate against taking action sooner rather than later lacks purchase.

[10] See Stern (2006), Nordhaus (2007), and Azar and Sterner (1996).

[11] The discount rate is thought to comprise a *pure* time-preference component and another part that reflects marginal utility of consumption that is expected to diminish with increasing levels of affluence (Arrrow et al., 1995; Fankhauser, 1994). Here our discussion focuses on the former.

[12] The exception being the subset of preferences that find expression in visceral reactions of the type, “I hate this, or love that.”

Changing views on smoking is one example of how our preferences change when our notion of the future consequences of our actions today changes. Few today doubt that smoking is harmful, including those who continue to smoke (CPPE, 2011). Once the future consequences of our actions are better understood, our subjective evaluation of costs today versus costs tomorrow also changes. The more pertinent problem is that this evaluation might not translate into change in behavior readily. Often when our "long-term" preferences change, our actual behavior might not, at least for a considerable time, and this might be the more important issue for economists to focus on.

The smoking example also highlights this problem. We know only too well that many smokers who want to quit perpetually put off quitting. They do not want to be smokers in the long run, but they keep smoking in the present. As is the case with *procrastination* more generally, procrastination involves a situation where the two sets of preferences, long- and short-term, are caught up in a perpetual clash. A smoker who knows that quitting is good for him or her might still dread the difficult adjustment cost it entails in the short run. Continuing to smoke (adaptation) involves rising future health costs and risks that can be alarming. However, these costs are mainly probabilistic, long run, and thus discounted, whereas the cost of quitting (mitigation) is certain and all front-loaded, which can make the smoker's discount rate an important determinant of when (and if) he or she will quit. For instance, public health messages that warn teenagers about the future health risks of smoking often fall on deaf ears because teenagers tend to heavily discount the future.

We clearly do not consider teenagers' high discount rate an unchangeable and inborn trait but a problem that needs correction, and when an adult discounts the future heavily we consider it a moral failing.[13] If we thought the *pure* discount rate was an immutable *given*, continuing to smoke for a time could then be shown to entail a net utility benefit. In fact, the higher a youngster's discount rate, i.e., the more "shortsighted" one is, the more an economist might advise smoking longer in the name of maximizing utility.

Counseling smoking teenagers not to be rash in quitting and arguing for delayed mitigation in climate change policy might have similarities. True, in the case of smoking, the relevant trade-off is between the well-being of the same person today versus tomorrow, whereas in the case of climate change it is between the well-being of future generations versus that of people who are alive now. In both cases, however, the well-being of the future self or future generations is very much dependent on what the present self or generations do in the present, which suggests that what we want for the future and do in the present can clash in a similar manner.

1.5. Short-Termism and Climate Change

Just as the typical teenager, the present generation can be said to have difficulty imagining a future that is fundamentally different from the present. This attitude tends to shrink the very time horizon that defines the *long run*. Consider the different time horizons involved in how the future or 'long-run' is conceptualized respectively by

[13] The older generation of economists clearly have thought so. Similar to Aesop's fable with *the grasshopper and the ant*, Irving Fisher wrote, "Generally speaking, the greater the foresight, the less the impatience and *vice versa*.... This is illustrated by the story of the farmer who would never mind his leaking roof. When it rained he could not stop the leak, and when it did not rain there was no leak to be stopped! Among such persons, the preference for present gratification is powerful because their anticipation of the future is *weak*" (cited in Akerlof, 1991, p. 6).

economists and climatologists. The long-run equilibrium of climatologists might take as long as a thousand years to materialize. It is a state where the climate forcing effects of GHG emissions and land use changes have stabilized and there is no further endogenous warming or cooling. By contrast, for economists it is hard enough to trust any long-run equilibrium model predicting 10 years out, let alone 100 years.

This unreliability of long-run economics models means that economists' models cannot possibly take into account the full long-run cost of climate change from a level of GHG emissions that upsets the ecological long-run equilibrium. The sea level in the new ecological equilibrium might rise, say, enough to leave only the Andes and Himalayas dry, but if that takes 1,000 years and we are looking at only the next 100 years at a time, the cost of mitigation might remain higher than adaptation in much of the 100-year intervals before reaching ecological equilibrium. When finally adaptation becomes the more costly option, climate might no longer be responsive to mitigation. One is reminded of the story of the frog too lazy to get out of the warming pond under the rising sun, finding a way to adapt to the increasing heat every step of the way until it boils to death. Economists might have something useful to say on why that happens and how such short-termism (procrastination) can be overcome.

Akerlof's (1991) analysis of the dynamic inconsistency between short- and long-run preferences in procrastination gives an idea why the proverbial lazy frog procrastinates to death. With a decision horizon that is exceedingly short, taking action now rather than later has a *salience cost*, giving rise to the inability - common to both the *lazy frog* and the *grasshopper* - to anticipate the future. If the cost of taking corrective action (say, quitting smoking) today is the same as tomorrow, both higher than its small short-run benefit, the salience of the immediate cost in the current period makes it more "costly" than undertaking it in the next. Thus, taking action tomorrow ends up being always preferable to doing so today. Our short-term preference is then caught up in a perpetual clash with our long-term preference.

In situations where we know this kind of a clash will occur, we often devise practical schemes to safeguard our longer-term preferences. Consider an example from Schelling (1984) with our twist on snoozing. Right before going to bed late at night, we want to wake up early in the morning and not be late to work, but at the same time we know quite well that come morning we will not want to get out of bed. In other words, we expect our long-term preference to come into conflict with our short-term preference in the morning, and predict that we will keep pushing the snooze button only to end up rushing uncomfortably or being late. As we press the snooze button to silence the alarm clock for few minutes at a time, our decision horizon is exceedingly short. At the end of the first snooze period, we decide to push the snooze button yet again because getting out of bed after the next snooze period is preferable to getting out now, and so it goes until we end up being late.

How do we deal with this problem? As Schelling remarks, one possible remedy is to put the alarm clock away from the bed to make it harder to delay getting up. Once taking action cannot be delayed with ease, the decision time horizon extends and the cost-benefit calculus then changes, and with it our myopic inability to anticipate the future is overcome. In more general terms, the moral is that dealing with procrastination involves finding a way to willfully constrain our freedom of choice/action in the short run such that it becomes easier to act on our long-term preferences, which we believe will make us better off (Akerlof, 1991; Schelling, 1984). In other words, when what appears 'optimal' from a short-run perspective is not so when looked at from a longer-run perspective, constraints on our short-run freedom of action to pursue what we desire to do might be in fact a blessing in disguise.[14]

What does this say about overcoming *collective* short-termism in climate change policy? At a cursory level, clashing long- and short-term preferences/interests in the realm of political decision-making is also commonplace. Governments the world over find their policy agendas shaped by pressing short-run political pressures that have urgent appeal for their constituencies, leaving little room to address long-term concerns that have little salience even if they are exceedingly important. Usually, political reforms that tackle long-term, structural problems become politically feasible only after a crisis.[15] Crises have this effect arguably because they reduce the relative salience of the short run by raising the public's attention on the long-term issues and problems that need to be addressed, which in turn, constrains the ease with which political power can elect to avoid taking steps that are politically costly in the short run. Again, then, constraining short-run freedom of choice (for inaction) makes it easier to serve long-term objectives.

At a deeper, more general level, however, arguments that generalize from individual behavior require closer scrutiny for they can run into two types of problems. One is fallacy of composition. What is true for the individual need not be so for the group as a whole. In the simple one-shot prisoner's dilemma game, for instance, individuals acting on what is optimal for them produce in the aggregate a suboptimal outcome. The

[14] In mythology, the story of Dionysius (Ulysses) and the sirens makes the very same point – see Elster (1977).
[15] Rahm Emmanuel's famous political dictum, "Never allow a crisis to go to waste. They are opportunities to do big things," captures this well. Quoted in Zeleny (2009).

other complication arises from the political and social determinants of collective agency. Even if a social optimum could be specified by simply aggregating individual preferences (the first problem), the nature of social divisions between groups/classes and the *rules* of political contention among them might render it unachievable (the second problem).

It is not unusual for economists to ignore both problems – especially the second one, which is occasionally taken up by non-Walrasian economists, old and new, on the fringes of the profession (Ertürk, 2012). Broadly speaking, we are inspired by this literature and draw on its insights to show in the next section how the consideration of a political/social variable (i.e., asymmetric power among countries/players) that bears on the second problem is integral to the outcome with respect to the first. The problem of *radical* uncertainty aside, cost-benefit analysis on climate change is not a purely technical exercise as economists tend to assume. Political constraints can often prove decisive in altering what course of action is optimal for the powerful agents whose decision matters, and it turns out *procrastination* can indeed be a helpful analogy in discussing how collective short-termism can be overcome. Using simple game theory, we show that the existence of asymmetric power is tantamount to the removal or absence of a short-term constraint that could have potentially constrained developed countries' freedom of choice in favor of inaction in the ecological short run and helped them act on their long-term interests. By implication, anything that changes the power imbalance can also alter what is *optimal*.

1.6. Collective Action, Asymmetric Power, and Climate Change

The power asymmetry between the poor and rich countries is a pervasive, essential characteristic of the world economy that shapes their multifaceted interactions, whether in the context of the global economy or the international political forums where terms of multilateral cooperation are typically negotiated. Yet, the ubiquitous nature of this asymmetry and the complex, multifaceted ways in which it manifests itself makes it hard to capture it in highly abstract, stylized economic models.

Here, we try to deal with this challenge by working with a simple, parsimonious definition of power asymmetry in simple game theoretic terms as to whether one's course of action has influence on the other players' payoff. The *powerless* can then be thought to face a one-dimensional prisoner's dilemma as what they do, defect or not, has no influence on the more powerful player's payoff. In our particular example, whether undeveloped countries choose mitigation (nondefection) or adaptation (defection) makes little difference to developed countries' well-being, and thus individually, each developing country vis-a-vis developed countries as a group finds itself in a one-dimensional prisoner's dilemma. By contrast, when developed countries follow a policy of adaptation (defection), undeveloped countries are liable to suffer the ill effects of warming regardless of what they themselves do.

In Figure 1.1, in (1A), both regions benefit from mitigation, whereas in (1B) developed countries get the superior *temptation payoff* from adaptation in contrast to the *sucker's payoff* the undeveloped countries receive. The disagreement between the economists and climatologists revolves around the question as to whether the temptation payoff (1B) is really preferable to (1A) for developed countries. In the shorter-run perspective of the economists, (1B) is superior to (1A), because developed countries can continue to benefit from growth at least for a time without paying an ecological price. Given their longer-term perspective, the reverse holds true for climatologists.

According to the climatologists, the likely outcome of adaptation in cell (1B) involves a *death spiral*. Warming rises beyond safe levels as powerful countries continue to externalize costs to the global commons. The vulnerable regions begin facing steeply rising ecological costs in the not too far-off future with prolonged droughts/floods and severe food shortages, both giving rise to heightened conflict over resources and an ever-increasing exodus of environmental/war refugees. In the meantime, as developed countries continue adapting to warming, some of the geophysical tipping points that accelerate warming are crossed. Warming settles on an unstable upward trajectory and the cost of mitigation proves inordinately higher than anticipated at the economically 'optimal' level of warming.

What could prevent this ascent towards the *death spiral* the climatologists fear is of course the question. This question is tantamount to asking what it would take for the powerful countries to act on their enlightened long-term self-interest and move from cell (1B) to (1A) in a timely manner. In our view, such a policy reorientation might entail a three-step process. The first involves a sea change in long-term preferences. Perhaps similar to how public attitudes towards smoking have evolved in the last few decades, we are arguably in the midst of a similar global transformation with respect to public awareness about the threat global warming poses for the future of the planet. As the public's awareness of the gravity of the threat extends, the second stage would be the growing recognition of the conflict between our short-term propensity to postpone corrective action and the planet's long-term well-being. This is the period of *procrastination* where the dynamic inconsistency between our short- and long-term preferences/interests results in the perpetual postponement of taking action. Finally, the third stage is when the conflict is resolved in favor of our long-term objectives when constraints are placed on our short-term freedom of choice for inaction in the short run.

Note that there is an essential asymmetry between (1B) and (1A) in terms of their respective implications with regard to collective action. All-out adaptation in (1B) requires no cooperation and developed countries end up acting as a bloc (vis-a-vis undeveloped countries) by merely acting on their individual short-term interest. By contrast, mutual mitigation in (1A) requires developed countries to agree on a mutually binding set of restraints on their behavior and, for it to be effective, an ability to sanction defection among their midst.[16]

Returning briefly to our smoking example, the smoker who is trying to quit realizes that resisting smoking *today* is worthwhile only if she or he will be able to resist the temptation *tomorrow* as well. Otherwise, incurring the cost of not smoking *today* will be a wasted effort. If the smoker has some credible reason to expect that some constraint will impede his/her freedom to backslide *tomorrow*, it becomes so much easier to *commit* to not smoking *today* (Schelling, 2006). In a similar dynamic, any individual developed

[16] For instance, given the voluntary nature of the Kyoto Protocol, there were no repercussions when both Japan and Canada failed to meet their commitments, which also brings up the question whether effective international obeisance can ever be achieved without active U.S. involvement even though its willingness and even ability to exercise leadership is increasingly in doubt. Interestingly, there are some tentative signs that opinion on climate change might be beginning to change within the U.S. political elite. A new study just released by the bipartisan *Risky Business Project* (RBP, 2014), and backed by former Treasury Secretaries Hank Paulson, Robert Rubin, and George Shultz, examines the financial risks of global warming with an objective to transform how American businesses and politicians (do not) think about climate change.

country that mitigates would incur costs in vain if other developed countries were to backslide on their commitment. Thus, in the absence of a constraint that can credibly be expected to impede backsliding by self and others, it becomes hard to commit to mitigation by any individual developed country in the first place.

Given that they happen to be in regions that are not immediately vulnerable to warming, the developed countries' crucial *short-run* freedom is their ability to externalize climate costs to the global commons. This externalization is made possible mainly by asymmetric power and, thus, the inability of undeveloped countries that are adversely affected in the present to deter it. It might be in the long-term interest of developed countries not to externalize climate costs, but the fact that they can makes it hard for each of them individually to commit to mitigation. When one powerful agent gives up its freedom to individually benefit from the weakness of the weak agents for some collective benefit, it has to be confident that the other powerful agents will do so as well. Otherwise, self-restraint simply enables another to profit at one's expense. This is the *commitment problem* of the powerful, and its solution requires a *commitment device* that would enable an individual *powerful* agent to credibly expect others to follow suit when it engages in self-restraint (Ertürk, 2011).

If undeveloped countries, however, were capable of changing the payoff matrix of developed countries through some concerted action, it could potentially work as a *commitment device* that would make it easier for developed countries to act in their long-term interest. Stylistically, if a coalition of undeveloped countries could reduce the developed country payoff through some retaliatory action, both groups of countries would find themselves in (2B) in Figure 1.2. With (1B) no longer attainable, (1A) would then become the preferred option for developed countries not only in the long run but in the short run as well. Collective *defection* by undeveloped countries could in this instance perhaps refer to something much broader – an ability to speak in one voice on climate policy in international forums that energizes activists worldwide, raising political costs for developed countries in the home turf through *striking*, *boycotting,* and public *shaming*.

To the extent that growing awareness of financial and economic costs associated with extreme weather patterns (IPCC, Core Writing Team, 2014)[17] and the spillover effects of climate-related calamities that are likely to begin unfolding in undeveloped countries in the not too distant future are transformed into *salient* politics at home, it is conceivable that the developed country payoff can change. If continued adaptation is thereby made politically and economically more costly by a block of undeveloped countries acting in concert, no individual developed country will be dissuaded from mitigation on account of fear of others' probable defection.

Clearly, whether undeveloped countries can act in concert, especially given that China and India might possibly favor delayed mitigation, and, if they did, what exact form their *defection* would take, are questions not easy to answer. At this point, we can only speculate. Though the comparison can be misleading, it is interesting to note that in the WTO's Doha trade talks, undeveloped countries did manage to act in a block (Kleimann & Guinan, 2011). Their collective ability to cause the collapse of the talks is an instance where they managed to reduce the developed country payoff to *mutual punishment* – (2B) in Figure 1.2 -- which might yet prove to be the strategic prelude to

[17] See also a report by the British nongovernmental organization, Carbon Tracking Initiative (CTI, 2013).

the achievement of a more equitable accord based on cooperation (1A) in the long run.[18] Coalition building (and maintenance) requires that players be able to (a) coordinate behavior, (b) monitor defection, and (c) bring political pressure to bear on defectors. Individual members can thereby not only coordinate and identify norm breakers more easily but also enforce rules within the group.[19]

There is also the possibility that developed countries can preempt or prevent any coalition building on the part of undeveloped countries by providing them incentives to break rank. Such a tactic would cause them to compete among themselves for what we might call the "scab's payoff," (2A) in Figure 1.3, in the form of financial and economic favors from developed countries in exchange for hosting their ecologically costly activities and legitimating developed countries' actions and positions in international forums.[20] The effect would be to keep most undeveloped countries locked in or return to (1B) in a one-dimensional prisoner's dilemma. In fact, anything that lowers the ability of

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[18] Climate policy is, of course, very different given that neither the terms nor the institutional framework of bargaining can yet be said to exist. Yet, future trade negotiations are likely to become increasingly enmeshed with environmental issues. Free trade agreements have been used on numerous occasions to dismantle environmental regulations at the local and national level (Klein, 2014, p. 69), and it is likely that they will continue to get in the way of efforts to address environmental concerns. On the other hand, while in principle, trade sanctions can potentially be effective in controlling carbon emissions, it is also true that environmental issues can be used opportunistically to raise entry barriers for developing countries in advanced markets (Esty, 2001).

[19] As a colleague who worked at the UN for many years put it, "When developing countries want something they try to have everything out in the open and when developed countries want something they work behind closed doors."

[20] See O'Brein and Leichenk (2000) for an extended discussion on how the financial/economic and environmental vulnerabilities of undeveloped countries can interact to their detriment.

the powerless countries to form coalitions and deal with free riders in their midst will increase the probability of returning to the *death spiral*.

1.7. Conclusion

We have argued that IAMs ignore how asymmetric power can skew the calculus of developed countries towards delaying mitigation. The distribution of climate costs around the globe is not just a geographic given but also an attribute of asymmetric power. The freedom to externalize their emissions to the global commons makes it harder for developed countries to overcome short-termism, just as it incentivizes undeveloped countries to act in concert to deter the former from passing their climate costs onto them. Thus, to the extent undeveloped countries can succeed in coalition building and act in concert, they can potentially help developed countries overcome ‘short-termism’ and act in their enlightened long-term interests as well.

Much of the policy discussion on climate change addresses the problem of controlling carbon emissions at a technical level, focusing narrowly on the instrument choice. Either emissions are to be capped at some level or the price of carbon is fixed through taxation. In the former approach, the quantity of carbon is fixed and its price varies with market demand, whereas in the latter, price is fixed and quantity varies when demand changes. The implications of these two basic approaches are then discussed in terms of their relative advantages and shortcomings, without, however, any real clarity on what the relevant criteria are. The usual utilitarian rubric economists traditionally use in choosing between different policy options is hardly satisfactory, at least when it comes to climate change. However, in the absence of an explicit discussion on an alternative, it tends to slip back into the analysis by default, which in our view is a critical lacuna in this literature.

Thus, the emphasis on the instrument choice ends up obscuring the more central problem of stipulating the normative and political underpinnings of collective welfare and choice. Two salient facts about climate change policy complicate the possibility of a neat separation between *normativ*e and *positive* analysis, a separation that comes natural to most economists. One, the policies that are taken (or not taken) today will have a decisive effect on the well-being of future generations, putting them possibly at peril; and, two, their costs and benefits are distributed very unevenly across agents currently alive per their relative position of power. Our discussion shows that the "optimal" policy is not independent of the outcome of the interaction of agents with asymmetric power, which in turn depends on the success of the power balancing efforts of disadvantaged and powerless agents acting on the basis not only of self-interest but also the strength of their normative values.

Developed Countries

	Mitigation (nondefection)	Adaptation (defection)
Poor Countries	*Win* (1A) *Win*	*Win* + (1B) *Lose*

*Figure 1.1***.** One-sided prisoner's dilemma.

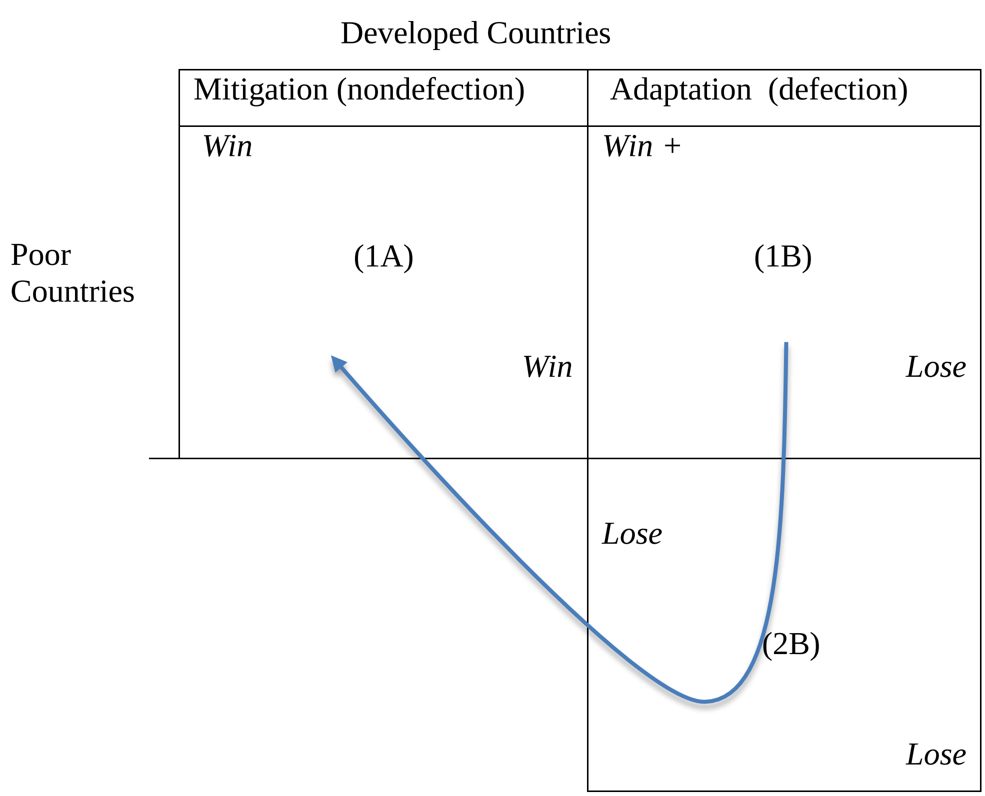

*Figure 1.2***.** Preventing the death spiral.

Developed Countries

		Mitigation (nondefection)	Adaptation (defection)
Poor Countries	(ND)	*Win* (1A) *Win*	*Win +* (1B) *Lose*
	(D)	*Win +* (2A) *Lose*	*Lose* (2B) *Lose*

Figure 1.3. Back to the death spiral.

CHAPTER 2

CONCEPTUALIZING ASYMMETRIC COSTS AND TIPPING POINTS: THE MACROECONOMIC AND CLIMATE CONFLUENCE

This paper attempts to frame asymmetric costs and tipping points associated with climate science and the economics of climate change in a stock model of post-Keynesian origins. Post-Keynesian dynamic models rely on stylized facts rather than representative agent microfoundations to explain macroeconomic phenomena. In this paper, climate science and findings from the economics of climate change are used to determine macroeconomic dynamics of a stock system (signs within the Jacobian), with a focus on powerful and vulnerable regions with respect to the costs associated with climate change. The paper attempts to answer how asymmetric costs and tipping points should be conceptualized for modelers and the implications such a conceptualization might have for the economics of climate change.

2.1. Introduction

The challenges that anthropogenic climate change presents to policy makers and academics are immense. Scientific and economic assessments often end with different conclusions as to the potential future costs, the ability of technology to combat future changes, and, perhaps most meaningful, at what level we should stabilize the climate system. Even more recent estimates (e.g., Nordhaus, 2010) using the integrated assessment modeling method (IAM), which is more pessimistic than previous cost estimates (Tol et al., 2003), still suggest allowing global average temperatures to rise by at least 3℃ from preindustrial levels. Climatologists warn of crossing tipping points in the near future (prior to a 3℃ warming in many cases), which would lead to major ecological vulnerability and greatly increase the likelihood of an ecological crisis (Hansen, 2008; Hansen et al., 2011; IPCC, Core Writing Team, 2007; IPCC, Core Writing Team, 2014).

The goal of this paper is to depict the dynamics of an economic system with an optimum capital stock close to a climatic tipping point in a world of asymmetric climate costs and economic/political power. In the second section, I will lay out some more recent estimates by both climatologists and economists of the future potential costs of climate change. These estimates lay the groundwork for assumptions to be made later on in the paper. Section 2.3 presents the structure of the model as well as explores the dynamics of various potential future outcomes. Section 2.4 concludes the paper.

2.2. Climate Science and Economics

2.2.1. The Future Costs of Climate Change

The future costs of climate change are difficult to estimate because future warming is uncertain,[21] and the impacts on economic activity are not immediately apparent outside of clearly climate-sensitive sectors, such as the agricultural and economic cost of disasters. How much warming the Earth is in for is uncertain because it is not known exactly where climatic tipping points are or precisely what the climate sensitivity is (the amount of actual warming a specific amount of CO_2 will cause). Another often-raised issue by the economists studying climate change is how societies will be able to adapt to the changes associated with climate change. The easier it is for a society to cope with the negatives of climate change, the more incentive there is to delay mitigation.

Nordhaus (2010) provides a baseline for the current estimation of the economics of climate change given the various policy scenarios being discussed. In his 2010 paper, Nordhaus uses his RICE (regional integrated model of climate and the economy) model (Nordhaus & Yang, 1996), which is a regionally calibrated model to estimate the costs of five climate policy scenarios. In his first scenario, he examines the costs associated with a policy that does not control for carbon. In this scenario, emissions grow very fast, reaching 793 CO_2 parts per million (ppm) by 2100 with a global average temperature gain of 3.5℃ by 2100 and 6.7℃ by 2200. This prediction is validated by the 2007 IPCC predictions and also means devastation for much of the ecosystem.

[21] How much warming are we in for? How much and when will positive greenhouse gas feedbacks affect the final outcome?

Nordhaus's 'optimal'[22] scenario predicts emissions will remain fairly flat over the next 2 to 6 decades, peaking in 2045 at 10 GtC CO_2 emitted per year. This case imposes a 50% reduction of 2005 emissions in 100 years. ppm CO_2 rises to 600 with the temperature rise peaking at 3℃ and then falling to 2.7℃ by 2300.[23] Nordhaus notes that he is referring to CO_2 ppm and not CO_2 equivalent ppm, thus ignoring other greenhouse gasses and, in doing so, probably underestimating warming. His peak of 3℃ warming associated with 600 ppm appears to be on the low end of the 2007 IPCC (the UN's Intergovernmental Panel on Climate Change) range; 3℃ warming given 600 ppm would be a good outcome for humanity given that stock of CO_2. Warming of 3℃ would probably produce an ice-free world, most likely facing strong positive warming geophysical feedbacks. It is also important to note that this economically optimal path requires immediate action in the next few years and decades.

Nordhaus's "temperature-limited" case is based on the limiting of warming to 2℃ above preindustrial levels,[24] which is the stated goal of the European Union, climate groups such as 350.org, and many others. The RICE model predicts flat emissions initially and then rapidly declining emissions after the next few decades. Emissions are cut by 50% by 2075 with ppm rising to 500 around 2050 and then declining and stabilizing around 450. According to the RICE, warming hits 2℃ and the price of carbon reaches 904$/ton of CO_2 by 2105 (again in 2005 dollars). According to the 2007 IPCC, it is more likely that ppm between 450 and 500 will result in 3℃ warming rather than 2℃,

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[22] From a cost-benefit perspective.

[23] I assume the reduction in temperature comes about from technological change, but it still does not seem to satisfy a James Hansen tipping point hypothesis.

[24] For Nordhaus (2010), this refers to 1900. Other studies use dates from 1870 to 1900 typically as a "preindustrial" reference.

with stabilized CO_2 ppm of 450 equating to a 2.8 to 3.2℃ warming within the 15-85% probabilities. This discrepancy might arise from focusing solely on CO_2 versus CO_2 equivalent.[25] Nordhaus highlights the difficulty in achieving the 2℃ limited warming goal: "imposing the 2℃ temperature constraint is quite costly, reducing the net benefit by almost half, because of the difficulty of attaining that target with so much inertia in the climate system" (Nordhas, 2010, p. 4).

All these estimates are still highly sensitive to the discount rate selected, as Nicholas Stern and others have pointed out (Azar & Sterner, 1996; Akerman et al., 2009; Pindyck, 2013; Stern, 2007). However, Nordhaus (2010) provides us with a fairly pessimistic estimate (for the economics of climate change that uses the standard integrated assessment model (IAM) methodology) as well as some key insights into the costs of climate change. If Nordhaus's estimates are correct, it appears that maximizing capital stock would take humanity beyond where many believe climatic tipping points lie.

2.2.2. Tipping Points and CO_2 Dynamics

Tipping points are nonlinearities in the climate system. Below tipping point thresholds, the climate system is sinking more radiant forces than it is emitting so the natural system acts as a sink for the global economy's anthropogenic climate forcing. The Earth's geophysical system is acting as a heat sink, preventing the full greenhouse effect from the CO_2 produced by humans. Once tipping points are crossed, the natural system ceases to act as a sink and begins to reinforce warming and atmospheric CO_2 concentrations (ppm). One commonly referenced tipping point is the methane frozen in

[25] There are many other contributors to climate change besides CO_2 such as methane and land use changes that Nordhaus ignores in his 2010 paper.

the Arctic tundra. Once warming reaches a point where the tundra thaws, the frozen methane will be released into the atmosphere (methane is also a greenhouse gas). Land use changes also contribute to this nonlinear dynamic in the natural CO_2 system, destroying carbon sinks such as forests.

Melting itself can be considered a tipping point. As melting occurs, it changes the Earth's surface reflectivity, known as surface albedo. When the Earth's surface is more reflective, warming will happen more slowly and the costs of warming will phase in more gradually and will be lower (it is assumed).[26] If the Earth absorbs more heat as a result of a larger area of ice melting, warming will happen faster, and thus costs will hit economies in a less spread-out and smooth manner.

Once enough of these positive feedback mechanisms are triggered, the natural CO_2 system will no longer sink the radiant forces that human-generated CO_2 causes. The natural system will begin to contribute greenhouse gases (GHG) and radiant forcing to the Earth's climate system, which will provide an additional warming challenge for humanity on top of the regular economic activity contribution. If stopping further warming will cost the world economy, after positive feedbacks kick in, those costs will come with interest.

2.2.3. Current ppm and Policy Towards Tipping Point Avoidance

Climatologists stress not crossing such tipping points. Avoiding tipping points should drive the policy debate (Hansen, 2008; Hansen et al., 2008, Hansen et al., 2011; IPCC, Core Writing Team, 2007; IPCC, Core Writing Team, 2014), which means

[26] Similarly to the way a dash shade in a car windshield keeps a car cooler in the summer.

stabilizing atmospheric CO_2 levels at 350 ppm in the long run, avoiding staying above such levels for too long (as we currently are at 400 ppm), and limiting equilibrated warming to 2℃ above preindustrial levels (implementing dramatic climate change regulation today). These suggestions might seem extreme to many economists familiar with the potential economic short-run implications, but Hansen et al. (2011) warn that there is still a great deal of uncertainty surrounding where safe levels are. The more we learn, the more sensitive the climate and tipping point dynamics seem to be. With this in mind, it is believed by many climatologists to be prudent to leave a margin of error and hold warming to 2℃ or lower if possible (which is associated with reducing atmospheric CO_2 ppm and stabilizing it at 350 or likely lower levels).

Modeling ecological catastrophes, such as an increased risk of mass extinction,[27] is very difficult for economists. Much of the modern developed economy is “not reliant” in a monetary sense upon agriculture or ecological systems, which seems to be an economic accounting problem and not a reality in terms of the economic system not needing the ecosystem to survive and function. Economists, even those using the general equilibrium framework, seem to be unable to place a significant economic cost on warming, leaving most economic studies to implement a partial equilibrium methodology for analyzing climate change costs, implying no significant spillover into global economic production.

[27] According to the 2007 IPCC report, a startling potential consequence of inaction is that, relative to a base period of 1980 to 1999, 20 to 30% of species assessed would likely face increased risk of extinction if increases in global average warming exceed 1.5 to 2.5℃ above preindustrial levels (still in the safe zone and likely even with action today at this point). If warming is allowed (or tipping points crossed that force warming to increase) to exceed 3.5℃, 40 to 70% of species assessed would likely face increased extinction risk.

2.2.4. Positive and Negative Externalities: The Disproportionality of Costs

Not all changes associated with climate change are economically negative. Some warming might increase agricultural productivity in higher latitudes, creating a temporary benefit for some regions in cooler climate zones (Mendelsohn & Schlesinger, 1999; Mendelsohn et al., 2006). Many regions have hill-shaped climate response functions, which means that as anthropogenic warming initially increases, some areas will see longer growing seasons, fewer spring frosts, and a CO_2 fertilization.[28] These gains, however, are most likely temporary, because with continued warming these gains will be reversed with conditions that are too warm and exhibit more severe weather, including droughts and desertification. With continued warming, the gains will not really be gains, but payday loans against future costs.

The distribution of costs in both time and space affects the economics of the estimation of what is optimal warming. Some regions of the world, such as sub-Saharan Africa and other lower-latitude regions, are already on the declining side of the hill .They are already too warm and too dry – and thus are currently experiencing an economic drag associated with climate change. The irony is that these lower-latitude countries tend to be the lower-emitting regions, whereas the higher-latitude regions (the most likely to at least initially benefit from climate change or not bear as many costs) are the regions that emit the most CO_2. For those vulnerable to climate change, the commons is already ruined.

If massive economic costs hit regions without developed economies, these costs would be less relevant to the bottom line in the cost-benefit analysis. If, for instance, the U.S. economy were 50% agriculturally based (as some African nations are) and also

[28] CO_2 fertilization refers to the extra resources plants have for growing with higher concentrations of ambient CO_2.

likely to face deteriorating agricultural conditions the way sub-Saharan Africa is expected to, the ‘optimal’ warming would be much different (Cline, 2007; Tol et al., 2003). Since climate costs are likely to hit economically marginalized regions more significantly in terms of scale to their economy, optimal global warming is likely to be higher. The U.S. agricultural share of GDP is between 2 and 3% (Cline, 2007; Tol et al., 2003). Less-vulnerable regions will receive a free ride from the vulnerable and economically marginalized segments of the global economy.

2.3. Two-Equation Model

2.3.1. Conceptualizing Asymmetric Costs Within a Two-Equation Model

Because of the way the costs associated with climate change are distributed across time and regional economies of the world, the economics of climate change ends up suggesting warmer optimal global temperatures. Costs associated with climate change are likely to impact the less-developed regions of the world first. Tol et al. (2003) suggest that sub-Saharan Africa and Southeast Asia will be the first and most significantly hurt. These impacts are due to the relatively warm temperatures they already have, given their lower latitudes, their higher dependencies on agriculture and climate-sensitive sectors, and their vulnerability to sea level rise. Larger, more developed economies are located in regions that are, for the most part, less vulnerable to climate change initially and therefore do not face immediate or direct costs at lower levels of warming. Larger, more-developed economies and regions also have better financing options for adaptive measures than their vulnerable, less-developed counterparts (Leichenko & O’Brien, 2008; O'Brien & Leichenko, 2000).

These costs will disperse throughout the global economic system in time. For now, the less-vulnerable regions are in the position of being able to emit without repercussions, whereas vulnerable regions face increasing costs and hardship now and into the foreseeable future. This relative position of power from a climate change cost perspective is not modeled well in the economics of climate change (Ertürk & Whittle, 2015). If this temporary lack of repercussions for the emitting behavior of powerful regions leads the climate system to cross tipping points, the system will be locked into an undesired positive feedback dynamic where warming continues with little human help (game over for growth).

To ensure that these model dynamics are represented accurately requires starting with the big picture, the long-run stock dynamics. Given the asymmetric costs and level of power that is clear in the world, we need to develop two models -- one model for vulnerable regions and another for powerful regions-- and place them in relation to one another. The models will show how the costs associated with the CO_2 system should look as economic activity drives stock levels of CO_2 higher and how the higher temperatures associated with the stock of CO_2 begin to drag on the economy.

2.3.2. Stylized Facts and Assumptions

The following models will rely on *stylized facts* (Kaldor, 1961; Ocampo et al., 2009, ch. 9) rather than using a representative agent and basing the Jacobian signs on microbehavior. The model will utilize our understanding of macroeconomics, climate science, and the economics of climate change literature to inform our assumptions of the individual systems behavior. This model will develop two systems, an economic system and an environmental system, both of which will be phrased in economic terms (prices and quantities). Both the economic and environmental systems will be a function of the other. The dynamics of each of the various components and phase spaces will be solved following Gandolfo (2010, ch. 18-21).

2.3.3. The Dynamics of ppm

If we were to look at the dynamics that climate scientist are trying to describe, we would discover a divergent system. The Earth's climate currently sits between two stable nodes, the Holocene equilibrium (preindustrial levels of CO_2) and the equilibrium humanity is pushing for, presumably when most of the carbon in the ground is back in the atmosphere as a result of human activity. The tipping points climate scientists refer to are unstable nodes, not an attractor but a point where the pull from the Holocene and the pull to the new higher ppm equilibrium are in balance. For the purposes of this model, we will simplify the notion of tipping points to just one tipping point. This simplification might seem to overstate the tipping point argument, but from a dynamic modeling point of view, it seems to be correct. Once climatic tipping points are crossed, changing surface albedo, thawing of tundra, and changing deep-ocean CO_2 content become push factors and provide additional climate forcing away from the Holocene equilibrium. φ will represent the concentration of atmospheric CO_2 (ppm) and will be used from this point on to discuss dynamics within the model.

The ppm dynamics will be simplified to avoid a full climatological model of emissions and feedbacks. It is important to remember that ppm concentration is the result of both environmental/geological dynamics and anthropogenic dynamics. $\dot{\varphi} = 0$ is the climatic tipping point: however, the divergent dynamic of the climate system will not be important for the stock model to be developed in the next section. Only in the conclusion will the problems of the tipping point be reintroduced. What is important about equation 2.1 is that the rate of CO_2 accumulation ($\dot{\varphi}$) is positively correlated with the level of CO_2 concentration (φ). The positive relationship between φ and $\dot{\varphi}$ is a fundamental finding of the climate science literature (Hansen, 2008; Hansen et al., 2009, Hansen et al., 2011; IPCC, Core Writing Team, 2007; IPCC, Core Writing Team, 2014). At a low level of φ, the climate system has room to absorb CO_2 emission. The sinking of CO_2 emission happens because of the dynamics discussed earlier such as plants, forests, and oceans. Since this is a simplified model of the climate system, the sinking behavior of the climate system can also include environmental and geological factors that suppress radiant forcing.

$$\frac{\partial\dot{\varphi}}{\partial\varphi} > 0 \tag{2.1}$$

The emission sinking is represented in Figure 2.1 by the section of the graph to the left of the $\dot{\varphi}$ axis (H in Figure 2.1). Equation 2.1 is important for the stock model in that it is one component of an environmental subsidy that will be developed and explored within the model. For now we can assume that the climate system resides to the left of the $\dot{\varphi}$ = 0 axis and that humans still can make meaningful mitigation decisions. Tipping point $\dot{\varphi}$ = 0 will become important in the conclusion of the paper as free-riding by powerful regions allows for φ to continue to increase beyond globally beneficial levels, potentially leading to an out of control downward spiral. To the right of the $\dot{\varphi}$ axis (I in Figure 2.1) is a region of the climate where human decisions become less relevant since the climate system itself reinforces warming. Region (I) produces an uncooperative economic system and thus makes it much harder for humans to bring CO_2 concentration back down.

2.3.4. The Two-Equation Model

ε represents the externalization cost of CO_2. If the benefits of productively emitting CO_2 outweigh the economic and environmental costs of emitting CO_2, ε will be negative. Negative externalization costs can be interpreted as a positive subsidy for emitting CO_2. If, on the other hand, the total costs of emitting CO_2 are greater than the economic benefits of emitting CO_2, then ε will be positive. Positive externalization cost can be interpreted as a positive tax. Figure 2.2 illustrates ε and how various values of ε should be interpreted. ε = 0 implies that the total costs of CO_2 emissions equal the total benefit of CO_2 emissions.

$$\varepsilon(\varphi) = \; Externalization\; cost\; of\; CO_2 \tag{2.2}$$

ε is defined as a function of φ, meaning that the externalization cost of CO_2 depends on the level of CO_2 concentration. ε depends on φ because of equation 2.1 and Figure 2.1. Since the environmental system sinks CO_2 differently at different levels of concentration (φ), the amount of cost the economic system will bear from its emissions will vary with φ. Equation 2.1 defines the manner in which the environmental system sinks CO_2 emissions. The higher the φ, the less $\dot{\varphi}$, implying there are fewer emissions from economic activity sunk by the climate system.

Equation 2.3 illustrates the fundamental finding of the economics of climate change. The externalization costs of CO_2 emissions (ε) are positively correlated with the level of concentration φ (Ackerman, 2013; Cline, 1991; Mendelsohn et al., 1999; Mendelsohn et al., 2006; Nordhaus, 1992, 2007, 2010, 2013; Nordhaus & Yang, 1997; Pindyck, 2013; Stern, 2007; Tol et al., 2003). As φ rises, so does the economic cost of emitting CO_2 (ε). Figure 2.3 illustrates this example. When the climate system is at a low φ, we know from expression one that the climate system is sinking a large amount of CO_2 emission. The large level of sinking at a low value of φ provides a subsidy to the economy by lowering the externalization cost of CO_2 emissions (E in Figure 2.3). The net effect of the climate system's sinking of CO_2 is that the benefits outweigh the cost of CO_2 emission and thus generate net negative costs (ε). At higher levels of φ, the climate system is no longer sinking enough CO_2 emission to make the economic benefits outweigh the economic environmental costs, thus generating positive (ε). At high levels of φ (F in Figure 2.3), the climate system is no longer providing a subsidy to the economic system; instead, the positive ε can be interpreted as a tax on economic activity that produces CO_2 emissions.

$$\frac{\partial \varepsilon}{\partial \varphi} > 0 \tag{2.3}$$

Of note at this point is that $\dot{\varphi} \neq \dot{\varepsilon}$, and $\varepsilon = 0$ does not correspond to the climatic tipping point. All that is required to generate the subsidy at low levels of φ and the tax at high levels of φ is that equations 2.1 and 2.3 hold. Since both expressions are nearly unanimously agreed upon within their respective research communities, it seems appropriate to make the assumptions of equations 2.1 and 2.3. Also eqautions 2.1 and 2.3 mean that humans can make meaningful cost-benefit decisions. If tipping points are crossed, these decisions might be meaningless as the climate system drags the economy kicking and screaming towards disaster.

The regions (G) in Figure 2.3 represent a post-tipping-points world where the level of φ has increased beyond the threshold climate science is warning about. Once the economic system crosses from (F) to (G), costs associated with climate change grow dramatically, and the stability of this stock model falls apart. It may be appropriate to interpret (G) as the regions where economies begin to have serious production problems associated with increasingly out-of-human-control climate costs. The increase in φ caused by the climate system itself (which happens in regions (G)) is not associated with a benefit, i.e., a productive use of carbon-based fuels. The extra costs brought on the economy after the climatic tipping point is crossed that are solely associated with positive feedback within the natural system are pure costs to the economy.

Equation 2.4 begins the development of a differential system where $\dot{K}$ is the growth rate of the capital stock. Capital accumulation (equation 2.4) is a function of the current capital stock and the externalization costs of CO_2. At an initial low stock level of φ, producing more φ has beneficial economic outcomes, as the costs from the additional φ are relatively low compared to the benefits received. In addition to the cost-benefit calculus being in favor of φ production when the stock of φ is low, the climate system has a tendency to sink additional φ, thereby giving the economy a bit of a free lunch temporarily.

$$\dot{K} = f[K, \varepsilon(\varphi)] \tag{2.4}$$

Equation 2.5 shows the externality cost dynamics. $\dot{\varepsilon}$ represents the accumulation of ε as a function of the K and ε. This isocline represents the diminishing cost sinking and eventually cost increasing dynamics of the natural system. The $\dot{\varepsilon}$ isocline can be regarded as the point where CO_2 emissions are neither adding costs nor sinking costs. The costs can, however, be externalized regionally at this point as will be discussed in later sections.

$$\dot{\varepsilon} = h[K, \varepsilon(\varphi)] \tag{2.5}$$

Equations 2.6 and 2.7 represent the Jacobians for the models for both the vulnerable regions and powerful regions.

$$Jacobian = \begin{pmatrix} \partial\dot{K}/\partial K & \partial\dot{K}/\partial\varepsilon \\ \partial\dot{\varepsilon}\,/\partial K & \partial\dot{\varepsilon}\,/\partial\varepsilon \end{pmatrix} \tag{2.6}$$

$$Jacobian\ signs = \begin{pmatrix} (-) & (+/-) \\ (0) & (-) \end{pmatrix} \tag{2.7}$$

Equation 2.8 represents the dynamic theory (Harrod, 1939) of the economic system and will always have a negative sign, with growth of the capital stock fluctuating around the warranted growth rate. This assumption makes sense since we do not typically see explosive growth or decay of the economic system. The sign assumption in equation

2.8 could change in the future with enough stress placed on the ecosystem, but for now and given our past experience, the assumption seems reasonable.

$$\frac{\partial \dot{K}}{\partial K} < 0 \tag{2.8}$$

Equation 2.9 shows us ε's effect on $\dot{\varepsilon}$ is negative in this model. This negative relationship is a behavioral economic assumption that represents cost minimization by economies. Equation 2.9 represents economies wanting to take advantage of the environmental subsidy (by emitting) and a desire to avoid the environmental tax (by reducing emissions). When ε is low, implying negative externalization costs of CO_2 (or environmental subsidy for emissions), $\dot{\varepsilon}$ is high; this can be interpreted as meaning the desire to increase costs is very high when costs are negative. In other words, economies want to accumulate negative costs. When ε is high, the externalization costs of CO_2 are in excess of the benefits of productively using CO_2; therefore, a cost minimizing economy would desire to decrease accumulation of positive costs. The $\dot{\varepsilon} = 0$ isocline is the point where the forces of costs minimization are in balance. Figures 2.4 and 2.5 show the environmental cost minimization dynamic.

$$\frac{\partial \dot{\varepsilon}}{\partial \varepsilon} < 0 \tag{2.9}$$

Three assumptions go into the sign of equation 2.9. First, equation 2.1 states that there is a positive relationship between φ and $\dot{\varphi}$, which is a general finding of climate science. Equation 2.3 states that there is a positive relationship between ε and φ, which means economic environmental costs rise with CO_2 concentration. Equations 2.1 and 2.3 create externalization costs that are negative at low φ and positive with externalization costs of CO_2 at high concentrations of φ. The natural system creates the economic subsidy or tax. The final assumption for equation 2.9 is that economies will try to accumulate environmental subsidy (negative ε) and diminish environmental tax (positive ε) in a manner consistent with standard cost minimization.

With equation 2.10 we see that, depending on whether a region is vulnerable or not to the costs of climate change, the effect of φ on capital accumulation will be different. Regions where capital accumulation is negatively affected by increases in ε have a negative sign for equation 2.10. In the global commons context, a negative sign will reflect a region that is being exploited by the powerful as φ increases. Regions where capital accumulation is positively affected by increases in ε have a positive sign for equation 2.10, meaning the cost-benefit calculus is still favoring capital accumulation. Powerful regions are not yet experiencing enough climate change costs for those costs to outweigh their benefits of continued capital accumulation and transfer costs within the global commons and thus have a positive sign.

$$\frac{\partial \dot{K}}{\partial \varepsilon} >< 0 \tag{2.10}$$

The sign for the capital stock's effect on the position of $\dot{\varepsilon}$ equation 2.11 is always zero because the physical climate system, equation 2.1, is not affected by the economy as far as altering the positive relationship between φ and $\dot{\varphi}$ [29]. However, the $\dot{\varepsilon}$ isocline, as we will see, will be in a different location for both the vulnerable and powerful regions, as their costs dynamics will vary based on their regional vulnerability and the makeup of their economy.

$$\frac{\partial \dot{\varepsilon}}{\partial K} = 0 \tag{2.11}$$

These dynamics leave us with two basic Jacobians. The first one shows the dynamics associated with the powerful regions.

$$Powerful = \begin{pmatrix} - & + \\ 0 & - \end{pmatrix} \tag{2.12}$$

The Jacobian for the vulnerable regions (equation 2.13) is signed below, where the costs of increasing φ are larger than the benefits. They are also not large enough emitters to shape the global ε growth path.

$$Vulnerable = \begin{pmatrix} - & - \\ 0 & - \end{pmatrix} \tag{2.13}$$

[29] This is a simplification that skews the results of the model in favor of capital accumulation and not climate damages. More recent work by climate scientists (Hansen et al., 2011) shows that the speed at which ppm is increased matters, and therefore the economy might have a significant effect when the positive warming feedbacks from crossing the tipping point are experienced.

2.3.5. Phase Space Analysis

Figure 2.6 shows the global phase space. Below the $\dot{\varepsilon}$ isocline, the value of this axis is negative, representing a negative cost for externalizing CO_2. Emitting activity has a subsidy placed on it by a forgiving climate system. Above the $\dot{\varepsilon}$ isocline, the value of the axis is positive, representing a positive cost for externalizing CO_2. Any emissions above the $\dot{\varepsilon}$ isocline will have a natural tax.

The horizontal axis represents the total capital stock. Movements to the right along the axis represent a larger amount of capital in the economic system. Technological change can be represented as shifts in the $\dot{K}$ isocline to the right, increasing the given capital stock at any particular φ (more on this in a later section).

Capital accumulation, $\dot{K}$ in Figure 2.6, is a nonlinear function as increasing ppm initially is correlated with increasing capital stock, but at a decreasing rate because of a beneficial cost structure. Eventually, increasing φ begins to shrink the capital stock as damages from warming are taking out more economic wealth than emitting is generating (above the $\dot{\varepsilon}$ isocline). The economic system's tendency is to continue to grow; however, the increasing costs associated with higher φ are an increasing drag on the economic system. Continued growth of φ undermines the growth of the capital stock and eventually causes losses in the capital stock, not just slowing accumulation. The tendency for a slowing and then shrinking economic stock can be associated with a loss of productivity in climate-sensitive sectors, costs of worsening natural disasters such as Hurricanes Sandy or Katrina, large-scale extinctions, loss of low lying cities, or lowering profit rates associated with rising costs of food and other economic system basic inputs.

The economic stock is stable around the $\dot{K}$ isocline, the warranted capital stock (Harrod, 1939). The stable path that makes the most sense is the $\dot{K}$ isocline, with costs adjusting as the economy grows. The $\dot{\varepsilon}$ isocline is also a stable path, but this path does not make much sense as far as the economics of climate change is concerned since we see a clear movement of φ and ε over time. Point (A) represents the environmental cost minimizing point for the globe. This is the point where the global economy would arrive (following the $\dot{K}$ isocline) that would maximize capital stock without incurring an environmental tax but taking full advantage of the environmental subsidy. Point (B) represents the maximum attainable capital stock of the global economy. Point (B) does not mean that the benefits of the capital stock at point (B) are shared globally; in fact the benefits of going from (A) to (B) are almost assured to be hoarded by some at the expense of others. Point (A) does not equal point (B) globally because of regional and economic asymmetric costs.

The movement (C) depicted along the $\dot{K}$ isocline from (A) to (B) is what Nordhaus (2010) predicts and what those countries that are less vulnerable to climate change would like to see. However, if the world did not have asymmetric costs and asymmetric power, the movement (C) would not be sustainable but for a brief period that would inevitably be followed by a corresponding period of decay back to (A). It is because of an asymmetric ability to exploit the commons and asymmetric costs of climate change that the movement (C) will become attainable.

2.3.5.1. Powerful Regions Phase Space

Figure 2.7 provides us with a look at the phase space of the powerful regions. This phase space differs from the global phase space in two key ways. The first is the position of the $\dot{\varepsilon}$ isocline for the powerful regions is at a higher level of φ, and thus the externalization cost of CO_2 is lower for the powerful at any given level of φ than it is for the vulnerable or globally. $\dot{\varepsilon}$ (powerful) equals zero at a higher temperature or φ than the $\dot{\varepsilon}$ (global) since the economies of powerful regions are less reliant on the ecosystem and have a geographical advantage compared to the rest of the world. The second way the phase space of the powerful regions is different from the global is point (B), the economic maximum, is a stable node. This system will converge on (B) eventually; the problem is that this is at a higher level of φ and thus flirting with crossing the $\dot{\varphi}$ isocline (more on this in a later section).

2.3.5.2. Vulnerable Regions Phase Space

In Figure 2.8, we see the phase space of the vulnerable regions. They are faced with a lower $\dot{\varepsilon}$ isocline than either the powerful regions or the global. Their economic optimum (V) may have already been passed given that they are already too hot and too dry (Cline, 2007; Tol et al., 2003) and are likely to face only worsening economic conditions going forward. Even though a vulnerable region's phase space might look like Figure 2.8 if the rest of world's phase space does not, there is little vulnerable regions can do to maintain the position of (V). They are likely to be pulled upwards in the phase space by the actions of other more dominant systems. The vulnerable regions might also have much flatter $\dot{K}$ isoclines as their economic outcomes are much more sensitive to changes in φ and ε. The vulnerable regions do not really have a choice between mitigation and adaptation. They have only one option individually: adapting to the powerful regions' emission behavior (Erturk & Whittle, 2015).

2.3.6. Dynamics, Comparisons, and the Commons

All systems are stable with stable paths along the $\dot{K}$ and $\dot{\varepsilon}$ isoclines. For all systems (global, powerful, and vulnerable), the economic system is convergent around some economically regulated growth rate, $\partial \dot{K}/\partial K < 0$. The externalization costs of CO_2 are stable around $\dot{\varepsilon} = 0$ due to cost minimization ($\partial \dot{\varepsilon} / \partial \varepsilon < 0$). The difference in these systems is the relationship with the global commons and how the environmental system impacts the economic system; for the powerful regions, the environmental system is still a positive in the economic system, whereas for vulnerable regions, it is negative, $\partial \dot{K}/\partial \varepsilon >< 0$.

In Figure 2.9, we can begin to understand how the movement (C) from (A) to (B) occurs in Figure 2.6. The $\dot{\varepsilon}$ isocline for the powerful regions is higher than the $\dot{\varepsilon}$ isocline for the global system, meaning that the powerful regions face lower costs for emitting CO2 at a higher φ. Since the powerful regions have a beneficial relationship with the global commons, the movement (C) represents their ability to externalize the additional costs to the commons. Moving from (A) to (B) is simply a matter of the powerful regions shifting costs via the commons to avoid facing the negative costs associated with crossing the vulnerable $\dot{\varepsilon}$ and the global $\dot{\varepsilon}$. The phase space in this system is still dominated by the powerful regions' $\dot{K}$ and $\dot{\varepsilon}$ isoclines; the stable node is (B). Because of asymmetric costs and power, we get dangerously high φ and globally unethical growth.

In Figure 2.10, we see the dilemma of the vulnerable regions. The vulnerable regions' economic optimum is at point (V), which is already below (A). They are today too hot and too dry and would still be exploited via the commons by (n) even if humanity avoided crossing the global (A). The vulnerable regions individually have no control over their climate destiny. Point (V) is thus completely off the table, and these regions are left to adapt to the decisions made by the rest of the world. If the powerful regions are able to push their system to (B), the vulnerable regions will be further exploited via the commons by an additional (n'). Even in Figure 2.10, (B) is the stable node since the only system that has control over its climate destiny is that of the powerful regions.

From Figure 2.10, we see that in a world with asymmetric costs and power, any aggregation via an IAM or other cost-benefit tool assumes a level of exploitation of the vulnerable regions. Even an IAM such as that of Stern (2007) that may produce an optimum of (A) assumes exploitation of the vulnerable regions and a redistribution of climate costs from those most able to absorb such costs to those least able to absorb such costs.

2.3.7. The Problem of Tipping Points

The ability to push φ to higher levels by the powerful's free-riding results in a potentially dangerous dynamic. Until now, we assumed $\dot{\varphi} \neq \dot{\varepsilon}$. We can still make this assumption, but consider what happens if ($\dot{\varphi} = 0$) is crossed. The vertical position of the $\dot{\varepsilon}$ isocline matters a great deal. If the tipping point ($\dot{\varphi} = 0$) is above the point at which the economic system is maximized (B), then there is some hope of avoiding a climate change catastrophe utilizing regular economic processes (capital accumulation dynamics and environmental economic cost minimization). The closer ($\dot{\varphi} = 0$) is to (B), the higher the risk of overshooting ($\dot{\varphi} = 0$) and leaving a cooperative environmental system. If ($\dot{\varphi} = 0$) is below (B), as many in the climate science community are warning about, cost shifting by the powerful becomes a very dangerous game that may lead to continually rising Y but with an environmental dynamic that is now uncooperative. Economies might want to mitigate and limit the growth of environmental costs, but they may be unable to alter the trajectory of φ and $\dot{\varphi}$. If the world were in a situation that did not have asymmetric climate costs, humanity would face increasing positive ε in a region of the phase space with a more cooperative natural system. The lower ($\dot{\varepsilon} = 0$) is, the more likely humans are to avoid crossing ($\dot{\varphi} = 0$), which may produce an ecological catastrophe that drags the economy down with it (region (G) in Figure 2.3). Since humanity is stuck with asymmetric environmental costs associated with climate change, humanity is also stuck with incentives to push φ higher.

A crisis of capitalism seems likely to emerge when the $\dot{\varphi} > 0$ causes out-of-human-control rising environmental costs with no costless solutions. At this point, increasing economic activity and dealing with the economic crisis by generating demand will lead to increasing emissions that will undermine any economic gains in the long run. Where accumulation ceases, it is unlikely that regular economic theory is sufficient to understand the problems facing the global economy. It is more likely that crisis theories become more applicable. It is hard to believe that the economic system functions smoothly in a period of prolonged crisis and that the $\dot{\mathrm{K}}$ isocline is symmetrical as ppm rises.

2.4. Conclusion

2.4.1. Extensions

Figure 2.11 presents an interesting potential extension of this framework. If we relax some of the assumptions of the model presented above, we can start to see some interesting dynamics that could emerge. If we remove the assumption of only one environmental tipping point but maintain that from a cost function perspective, there is still some $\dot{\varepsilon}$ isocline that represents stable costs with all of the aforementioned dynamics, and we might see a movement (D).

As the environmental system crosses its tipping points (one at a time, for instance, moving along φ), we would probably see the $\dot{\varepsilon}$ isocline lower, as the stable cost dynamics of the phase space would have to account for the increasing costs of crossing the latest environmental tipping point. Figure 2.11 requires not only relaxing the single hypothetical tipping point assumption but also introducing time in a meaningful manner. The order of events would become important, and thus the system would take on a path dependency, not unlike the actual climate and macroeconomic systems. An additional difficulty that would be required to work out would be the issue of $\partial\dot{\varepsilon}\,/\partial K = 0$ no longer equaling zero.

These mechanics have yet to be worked out, but they do seem quite interesting and suggestive that overshooting the Earth's carbon budget requires not only a return to the stable emission levels of a pre-overshoot world (probably less than A), but also the implementation by humanity of emissions restrictions beyond such a point, to (A'). If climate stability is a goal in the future, any trips across the stable point could imply long-term continuous costs well in excess of any short-term gains.

2.4.2. The Collective Action Problem and Closing Thoughts

The collective action problem illustrated clearly in Figures 2.9 and 2.10 shows the precariousness of society's situation. Pursuing a policy of maximizing economic costs/benefits by powerful regions leads the world closer to the bad half of CO_2 divergence ($\dot{\varphi} > 0$), and any gains are likely temporary and not shared. Going from (A) to (B) is easy once asymmetric costs are understood. Going in the opposite direction seems to be a much more troubling macroeconomic dynamic. Economists are concerned with the maximum achievable capital stock (B). However, the ethical concerns about the levels of international exploitation are serious when one goes from (A) to (B). Vulnerable regions are already disadvantaged: (n) in Figure 2.10. Further exploitation by the powerful regions (n') does not seem justified given the powerful regions are already typically high-income regions that gain little in terms of quality of life by increasing their material wealth. Redistribution of material wealth down the international income scale and stabilizing the climate system at 2℃ or less is the only justifiable course of action.

The only means the vulnerable regions have to redress this level of exploitation is coordinated collective action. The vulnerable regions acting as a bloc could use trade sanctions, embargos, and public shaming to impose the costs dumped into the global commons on the powerful regions. These actions may be enough for the powerful regions to readjust their economic optimum and prevent humanity from over-drawing our carbon budget. A readjustment of the powerful regions' economic optimum could also force economists studying climate change to analyze what kind and how much redistribution of power and capital are required to reduce the impacts of moving to a safe economic size given our current technology and population. Socializing global investment in technologies not only increases efficiencies but also might lead to substantial decoupling with large enough economies of scale to facilitate a complete end to carbon-based fuels. Any solutions that prevent carbon overreach will require an antineoliberal movement to reassert the state and its ability to control the market by a coordinated coalition of the vulnerable regions.

2.5 Appendix

2.5.1. Technical Change

The economic system's position relative to the $\dot{Y}$ isocline is very much dependent upon the technique of production and the technology used. If, for instance, reliable low-energy nuclear reactions (LENR) became an economic reality, then we would be taken off this phase space entirely. If the usage of carbon-based fuel is decoupled from CO_2 emission to a large extent through the use of more efficient and lower cost renewables, the economic stock optimum will be attainable with less ppm, as Figure 2.12 shows (B) to (B*).

The gain illustrated in Figure 2.12 assumes a small or even nonexistent rebound effect[30]; such a movement would require technological gain coupled with taxation policies to remove the incentive to increase consumption of CO_2.[31] Thus, technology alone is not going to solve this problem, and there is a need for political action (Greening, Greene, & Difigilo, 2000). Only the most optimistic would believe that technological game changers will arrive in time to avoid having to make some hard choices as to mitigation and adaptation policies as we are already above the safe $\dot{Y}$ line. Nuclear power will have to overcome serious public image and safety/cost problems. LENR is viewed by most as science fiction.[32] Renewables have serious problems with storage, reliability, and costs. Therefore, it seems like a grand policy will be required even for the most optimistic.

[30] Rebound effect dynamics are estimated in Figure 2.12.
[31] These dynamics are estimated in Figure 2.13.
[32] Even if NASA and SPAWAR (Marwan et al., 2010; SPAWAR), Szpak, Mosier-Boss, and Gordon, 2007 (SPAWAR) and Bushnell (2010; NASA)) seem to take it seriously.

2.5.2. Rebound Mechanics

Figure 2.13 represents what a pure rebound effect (Jevon's law) might look like. The technological change that produces resource efficiency gains also generates a lower cost per unit of production, since the energy input will go further in the production process. These cost dynamics can generate greater consumption of resources than previously. For example, improvements in the steam engine led to greater coal consumption in 19th-century England.

For the climate crisis, a contemporary example is the increasing fuel efficiency of automobile engines, which has not led to a decrease in year over year ppm production by transportation but rather allowed driving to remain a very cheap means of transportation in spite of rising fuel costs. In this case, we would expect an outward shift in the $\dot{K}$ isocline. The economic system should be able to achieve equivalent or greater output at point (A) than previously at point (B*) and still be ecologically safe. However, the efficiency gains lead to greater consumption of the resource rather than less as the economic maximum is now at B. Instead of going from (B*) to (A) as the engineer intended the system to go, the economic system ends up at (B), producing more ppm than previously.

In their article on the rebound effect, Greening, Greene, and Difigilo (2000) point out that policy will always be required along with resource-efficient technological change. Such policies, such as a carbon tax, will discourage increased use of the resource due to a lower unit cost, and the efficiency gains will still have a positive effect on the economy. We can see this with Figure 2.14, a phase diagram where the $\dot{K}$ isocline initially moves to the right with the positive technological change and a tax policy then shifts the $\dot{K}$ isocline down, creating a situation where the economics optimum is at (B tax) and ecologically safe. The efficiency gains from the technological change allow the economy to be larger in areas with less of an impact on ppm, thus increasing the capital stock and not expanding areas of the economic system that place an additional burden on the climate system.

2.5.3. Growth or No Growth?

There is the question of how this model fits into the growth/no-growth debate. This model is only a no-growth model under a specific set of circumstances. If we assume no technological improvement in efficiency or a very strong rebound effect, then it is a no-growth model. The other assumption would be that population grows faster than the decoupling rate that technology provides. Both arguments are legitimate. Population seems to be a primary driver of climate change and is also so taboo for politicians that it is unlikely any policy will be implemented on a global scale. We do see relative decoupling in the global macrodata, but we do not see an absolute decoupling that suggests an active rebound effect combating efficiency gains over the past 30 years (Jorgenson & Clark, 2012). These two exceptions seem to have been the sticking points of the growth/no-growth debate for years now (Daly, 1974; Solow, 1973), and it is not likely this model will do anything to settle the debate.

The main insight of this model remains intact regardless of whether or not it is a growth or no-growth model. The policy question from an economics perspective needs to be reframed from one of maximizing growth and potential capital stock to one of avoiding tipping points and staying in a scientifically determined safe warming region.

As technology changes or population changes, those tipping points stay the same, and thus the economic problem becomes one of optimizing given a constraint (staying in the safe warming region), a not too unfamiliar concept for economists.

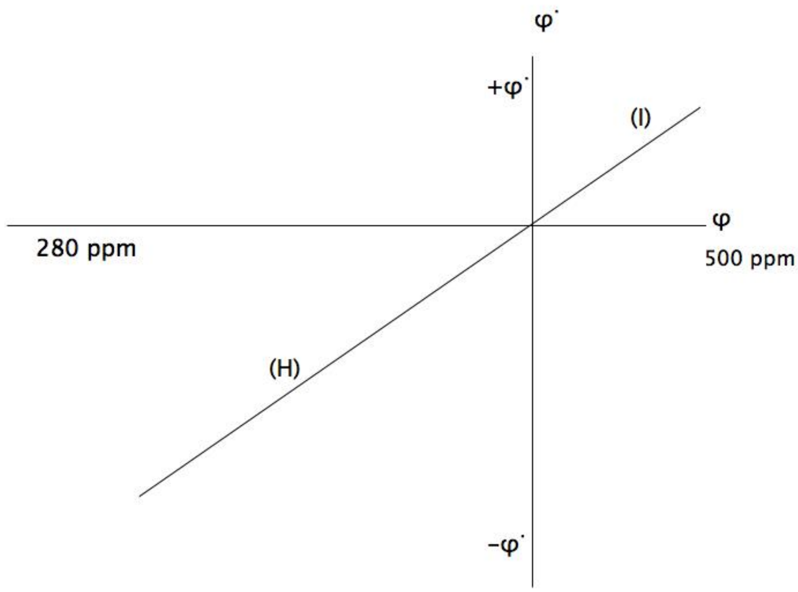

Figure 2.1. The dynamics of the environmental system.

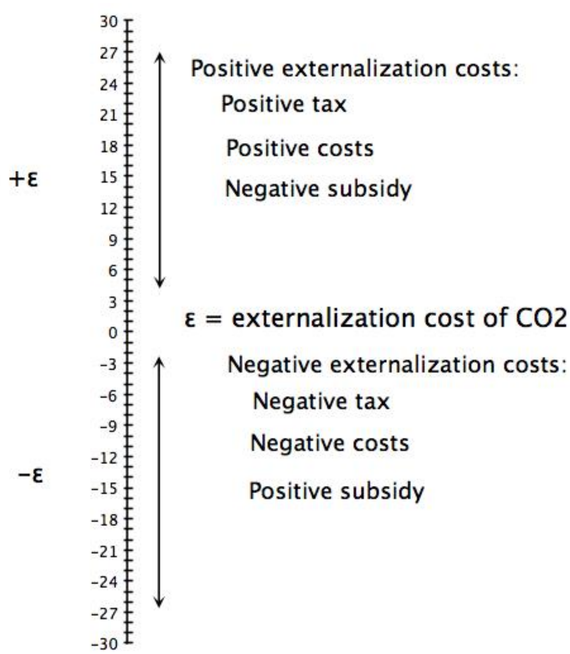

Figure 2.2. $\boldsymbol{\varepsilon}$ interpretations.

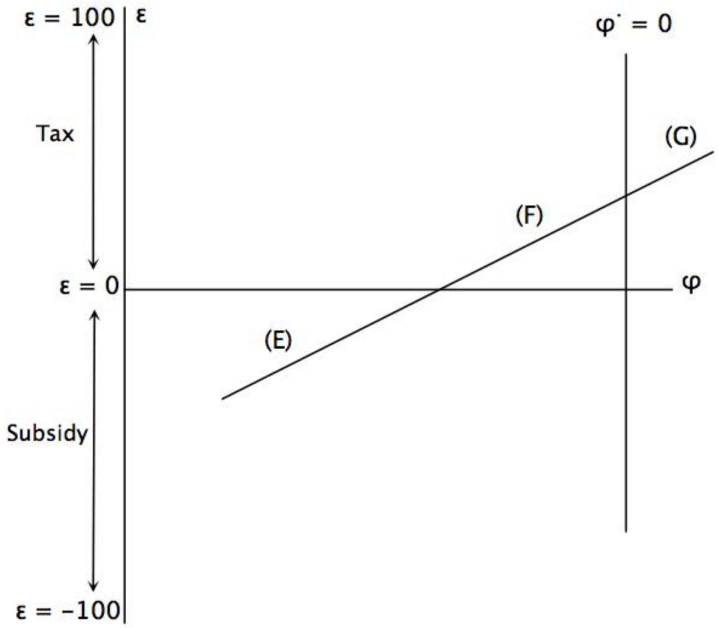

*Figure 2.3***. *ε*** has a positive relationship with ***φ*.**

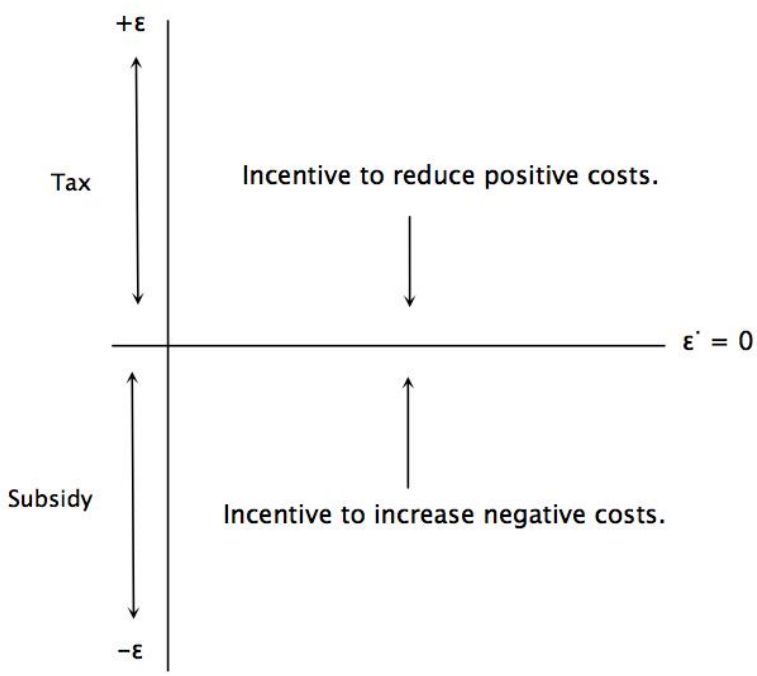

*Figure 2.4***.** The dynamics of cost minimization of ***ε***.

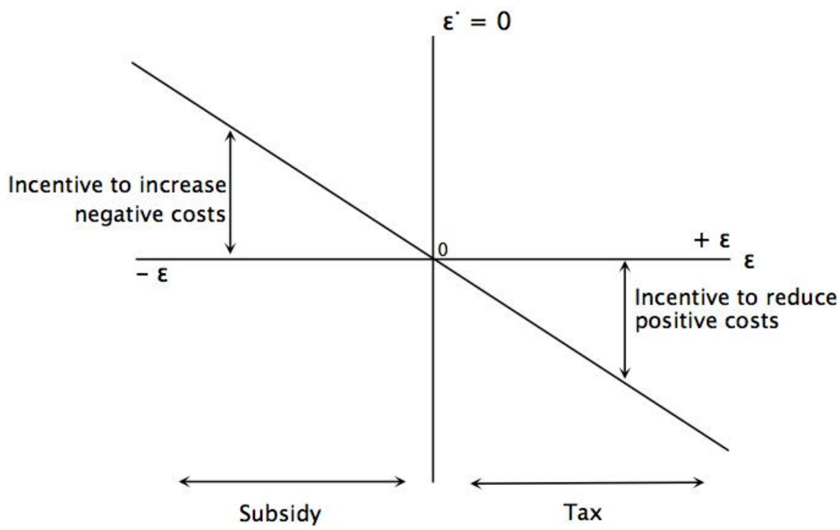

Figure 2.5. The dynamics of $\boldsymbol{\varepsilon}$ and $\dot{\boldsymbol{\varepsilon}}$.

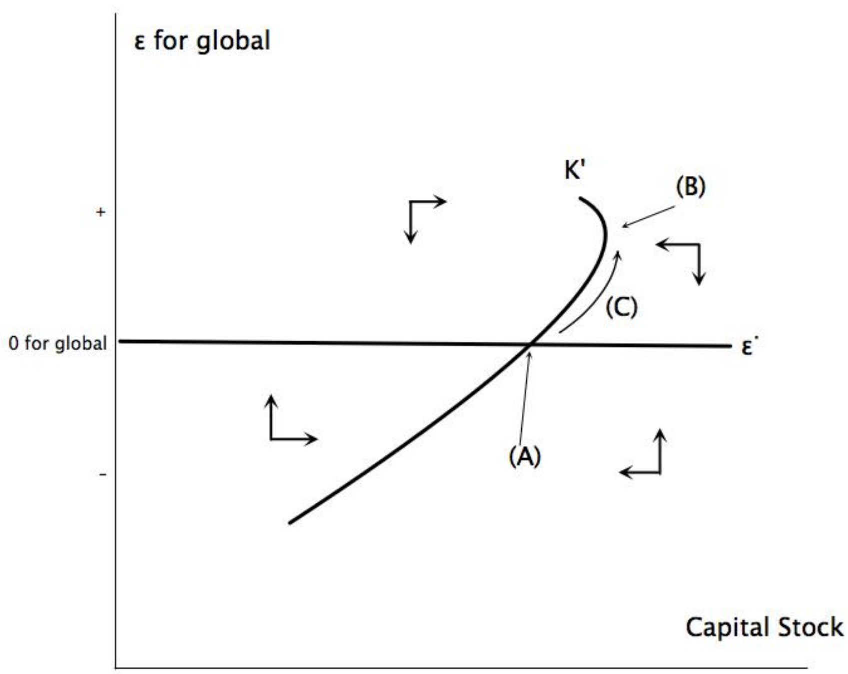

Figure 2.6. Global picture.

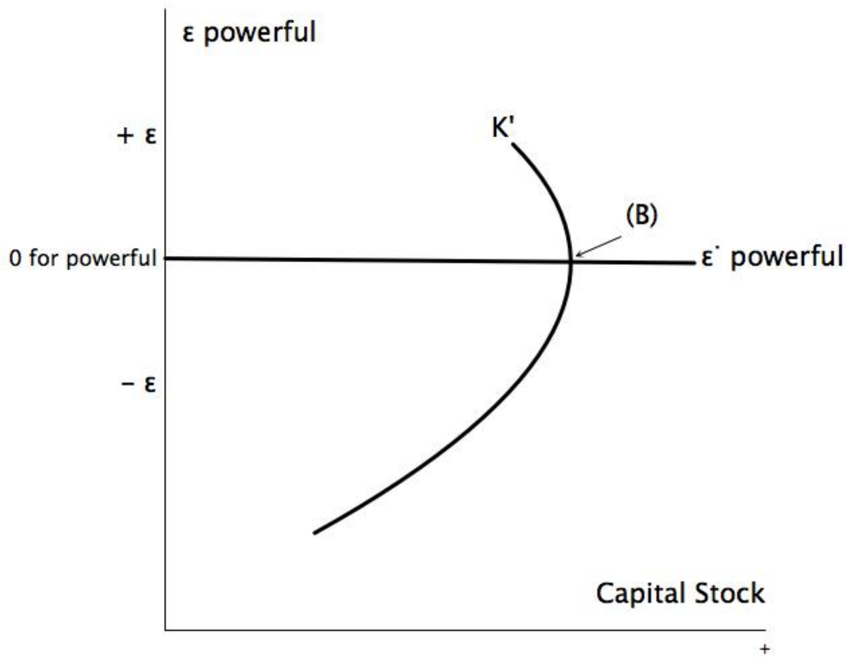

Figure 2.7. The powerful regions.

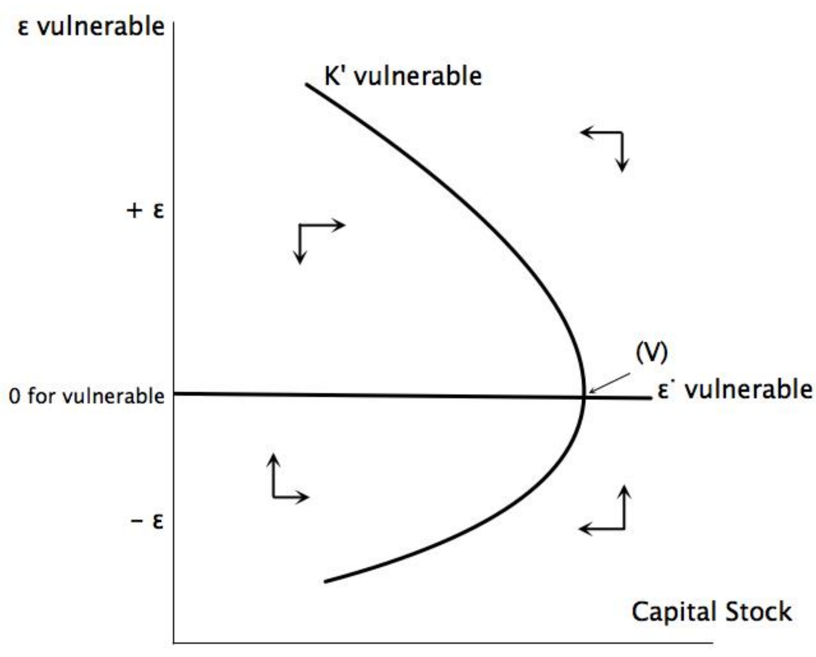

Figure 2.8. The vulnerable regions.

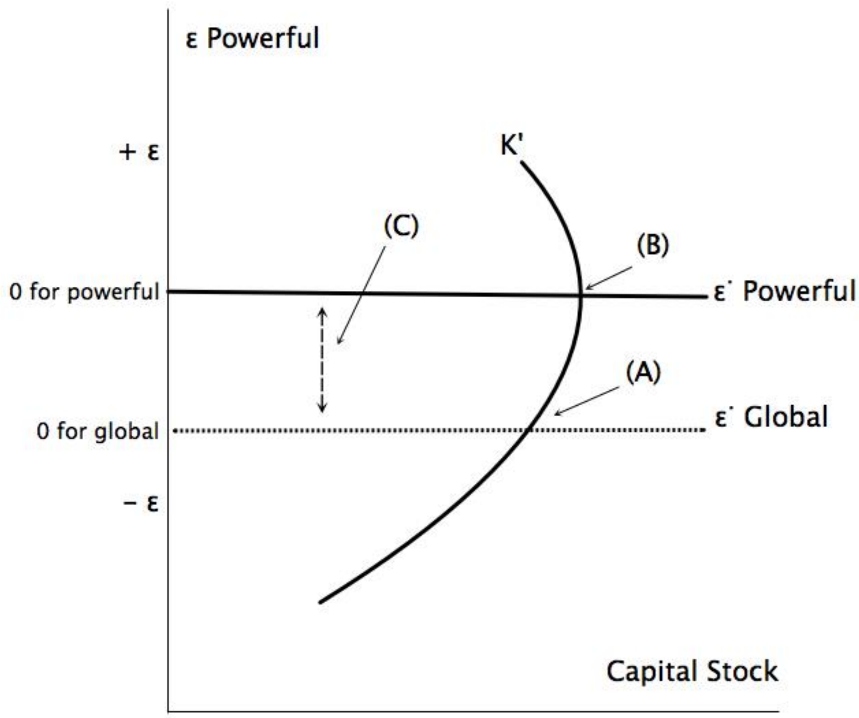

Figure 2.9. The powerful regions' relation to the global.

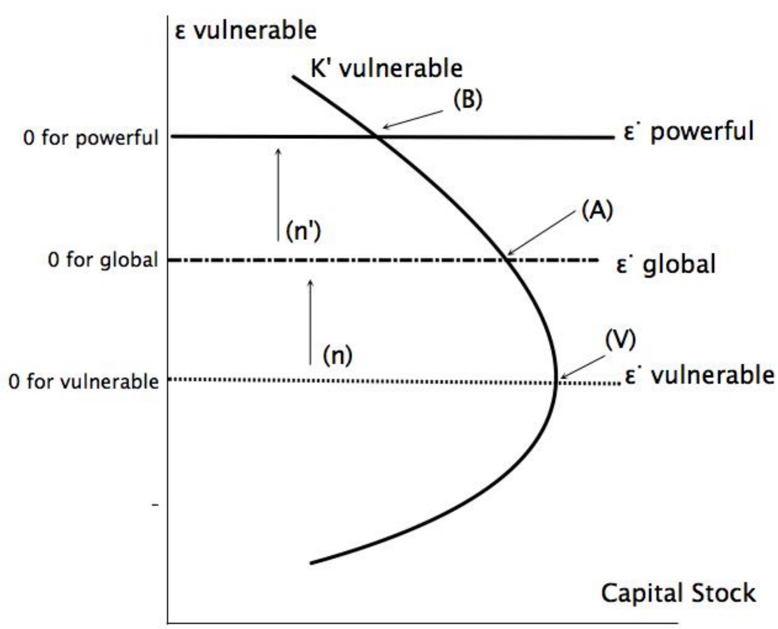

Figure 2.10. The vulnerable regions in comparison to the global and powerful regions' cost functions.

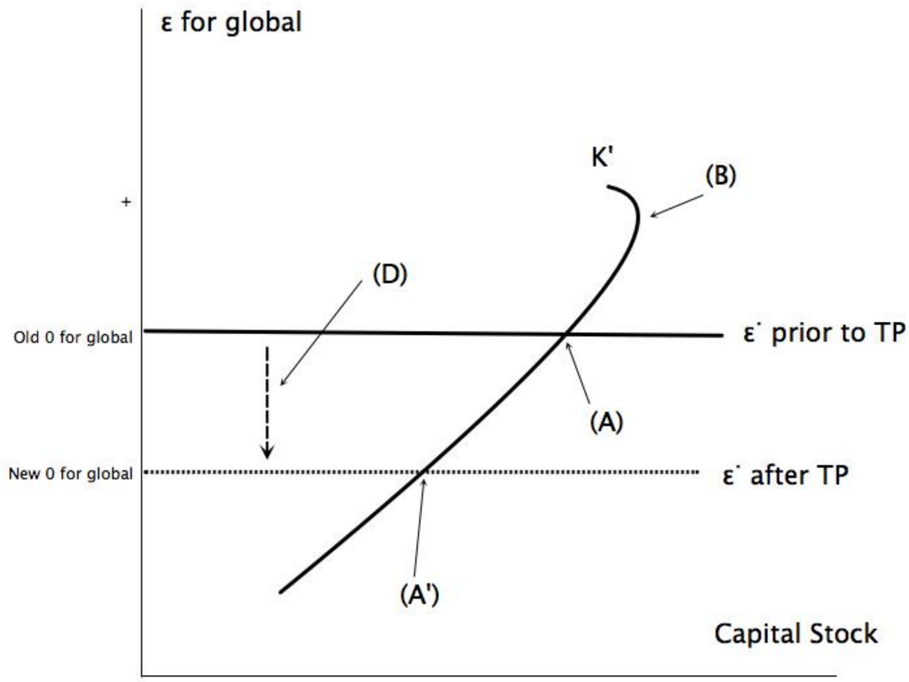

Figure 2.11. A dynamic cost curve.

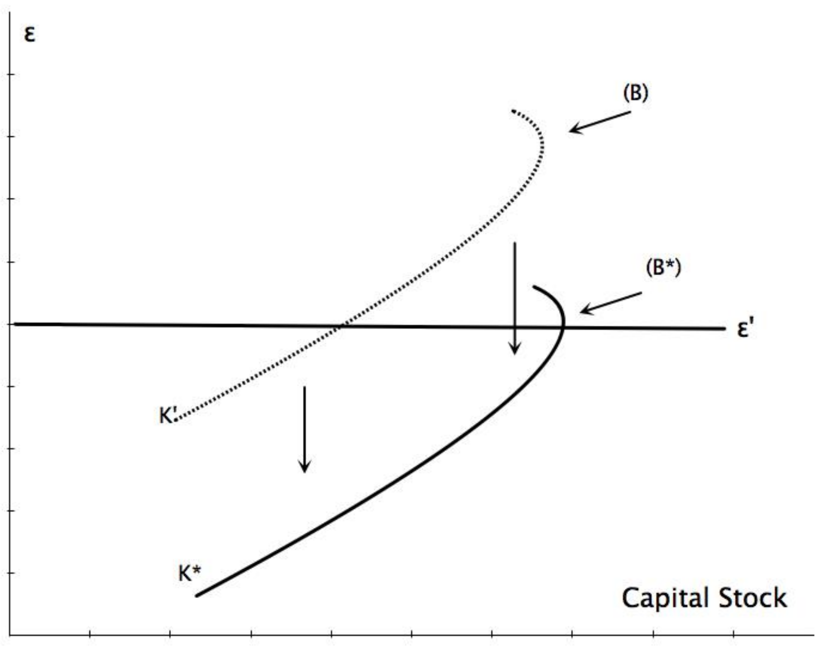

Figure 2.12. 'Green' technological change.

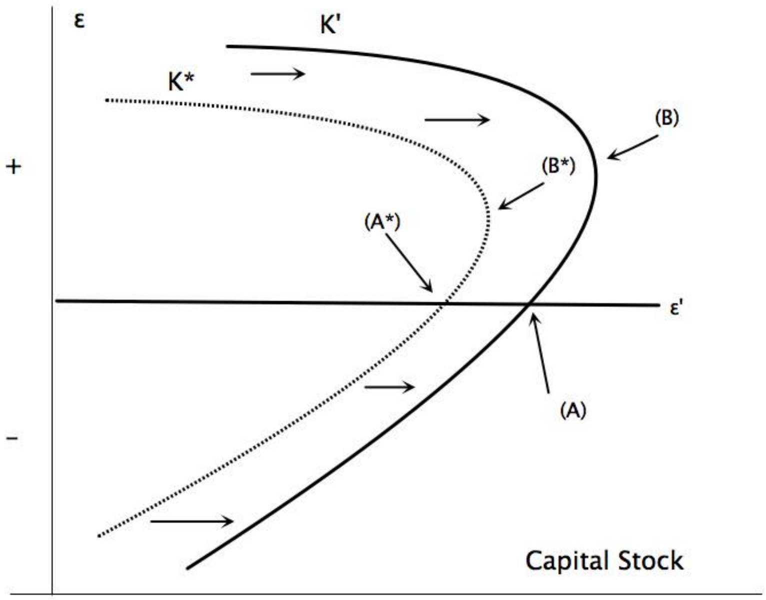

Figure 2.13. Pure rebound effect.

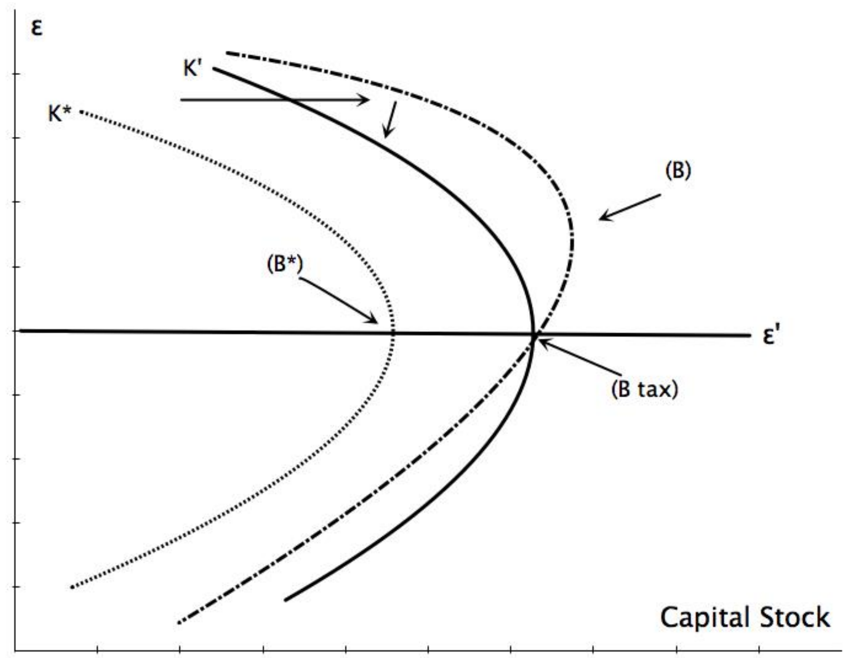

*Figure 2.14***.** Rebound effect with tax.

CHAPTER 3

BAYESIAN UPDATING ROLLING REGRESSION ANALYSIS OF DECOUPLING DATA: 1970-2010

3.1. Introduction

This paper explores the relationship between economic activity and global CO_2 emissions using new data and a methodology new to the field. Capitalist economic growth is inherently harmful to the environment and leads to the depletion of natural resources and the exploitation of the global commons. It is vital to understand this process as much as possible and determine where changes can be made to this basic dynamic. As macroeconomics continues to develop a theoretical understanding of global environmental problems, empirical work is required to lay a foundation of knowledge. The most basic relationship that is studied is *decoupling*; how does the link between environmental degradation and macroeconomic growth change over time? Proper estimates of decoupling are useful not only for theoretical macroeconomics but also for practical global environmental policy, which relies on good estimates of baseline behavior. Decoupling refers specifically to getting more economic 'good' for less environmental 'bad'. This is a very intuitive idea, as with increases in technology, education, and experience, one would expect that decoupling would naturally occur over time. There are, however, economic forces to contend with and bouts of strong economic growth, which might make this rather intuitive concept empirically less relevant.

Climate change is the ultimate example of the ecological dynamic of economic growth. Industrialization requires industrialized power generation. Modern (the past 150 years) power generation, which has fueled the explosion in economic growth, has relied on using up natural resources. Climate experts advocate 3-6% per year reduction in CO_2 emissions. CO_2 reduction would be a large enough challenge on its own if the economy were not growing, but then consider that the global economy grows by 2-3% a year. This paper continues the examination of decoupling CO_2 growth from economic growth, using global times series data, to shed light on the robustness of decoupling analysis and open up new avenues for macroeconometric research. This paper employs a Bayesian updating rolling regression to access the stability of the CO2 to GWP (gross world product) relationship. Three models trace the same dynamic through the data. A massive decoupling event occurred in the mid-90s as a result of the collapse of the Soviet Union, followed by a surge of carbon intensity in the 2000s with the rise of China and India. These large exogenous shocks to the data leave some doubt as to whether or not decoupling is occurring at all as the parameter estimates in the mid-2000s are roughly the same as the estimates prior to the collapse of the Soviet Union.

3.2. Decoupling Studies: Insights and Expectations

The environmental Kuznets curve (EKC) literature is well developed at this point (Grossman & Krueger, 1991; Stern, 2004). The EKC theory "is a hypothesized relationship between various indicators of environmental degradation and income per capita" (Stern, 2004, p. 1419). Empirically, this theory predicts that as income per capita rises from an initially low and underdeveloped state, environmental degradation will rise. Economies are moving from low-energy-intensive, low-pollutant-intensive, agriculturally based production to higher-energy and pollution-intensive production, and manufacturing. This part of the hypothesis is not controversial. Many within the field of ecological economics and even Marxist ecological critiques of capitalism would agree with the theory so far (Daly, 1997; Foster, Clark, & York, 2010; Li, 2008). EKC theory further predicts that as income per capita rises, economic growth has a smaller impact on the environment. The reasoning from the EKC literature is that with the extra income per capita, society is now affluent enough to value environmental quality as well as other economic needs. The economy transitions to an "information-based" economic structure rather than a manufacturing structure, thus leaving a smaller environmental footprint. This decoupling of the impact of economic growth on environmental degradation is the controversial part. According to Stern (2004), this claim has not been grounded in reliable econometric empirical work.

The EKC literature has primarily utilized panel data methods, which present an unclear picture (Kijima, Nishide, & Ohyama, 2010; Stern, 2004). Panel methods are used primarily to capture different economies at various stages of economic development and income. Using a panel shows whether or not countries begin to value environmental quality more and more as the economy develops and attains a higher level of affluence. The econometric results are quite sensitive to the countries selected to make up the panel (Kijima et al., 2010), most likely because as an economy develops and transitions to an 'information-based economy,' it off-shores its dirty manufacturing processes rather than decoupling.

If an analyst selects developed countries that are off-shoring dirty manufacturing processes and does not select the developing countries that are picking up those dirty manufacturing processes, it may appear that decoupling is occurring. In reality, this is just a shifting of environmental degradation around the world. For instance, dirty manufacturing processes in China are supporting consumption in the U.S. U.S. consumers may still be very dirty, but much of the environmental degradation they are responsible for is transported to China.

For the purposes of climate change, the development of an individual country is of little consequence. Even if the EKC theory were correct, humanity might not have enough time to wait for all countries to develop sufficiently to begin significant decoupling of CO2 and GDP growth.[33] Kijima et al. (2010) point out that there is also an assumption in much of the theoretical EKC literature that both sides of the hypothesized environmental degradation/income per capita curve are symmetrical. It seems likely that the curve would be steeper in the beginning phase of economic development when incomes are low and capital formation is in its early stages and much flatter for the developed phase when lifestyles are focused on high consumption, meaning that a much longer time and higher income would be required to reverse environmental degradation.

The contributions this paper makes to this literature are starting from a global time series rather than panel data perspective and explicitly discussing the various

[33] Steinberger and Roberts (2010) estimate with the human development index that there is time to achieve increases in HDI and that decoupling can go hand in hand with development. In contrast, some suggest, "without systemic changes, green goals and full employment are incompatible" (Antal, 2014, p. 284).

elements and scale of uncertainty involved with empirical decoupling studies. This paper's analysis does not suffer as much from country selection bias, as the focus is on global aggregates. This aggregation goes a long way toward eliminating the off-shoring problem in much of the EKC literature while sacrificing country-specific idiosyncrasies.[34] Aggregation has trade-offs and is far from perfect, but it is better at measuring global decoupling and providing insight into global policies. Because our analysis focuses on global aggregates, it will be implicitly dealing with total levels of pollution rather than pollution per capita. Per capita emissions are vital for policy work and understanding the underlying distributional dynamics of the global commons. Per capita emissions have their place in empirical analyses that retain country-specific characteristics. However, using a global time series washes out the country-specific characteristics such as emissions per capita, so including per capita emissions in this analysis would not add any information.

In the context of climate change, relative decoupling is a slower growth rate of CO_2 or greenhouse gases (GHG) than the faster growth rate for the economy (GDP or GWP). Relative decoupling is clearly a welcome occurrence, but it is also potentially irrelevant if the ecosystem requires a stop to emission growth altogether.[35] With relative decoupling, as the economy grows in size so does the stock of pollution even if both variables are decoupling from one another. This is a large problem for climate change:

[34] Eric Sjöberg commented that this does not, however, completely eliminate the 'off-shoring' effect since it is likely data collected from less-developed countries are less reliable than data collected in developed countries. If an advanced economy off-shores some 'dirty' processes, there is likely a loss of data, or at least less precise data.

[35] Antal (2014) discusses estimates ranging from 3-6% year over year declines in CO2 being required to avoid potentially devastating climatic tipping points. The decline in CO2 also has to compensate for a growing global economy.

the absolute level of global GHG pollution needs to come down (currently greater than 400 ppm). This paper's data analysis speaks directly to these issues of scale and global impact.

Some empirical work looking at GHG emissions finds theoretical ambiguity. Jorgenson and Clark (2012), using an extensive panel study constructed with care to avoid off-shoring effects, find evidence of some relative decoupling along with evidence of "mini-cycles" of decoupling and intensification over time while overall CO_2 continued to rise over time. Steinberger and Roberts (2010), using a previous iteration of the CO_2 data that are used in this paper, find evidence of decoupling of CO_2 from Human Development Index (HDI) indicators; however, their study does not include any significant robustness checks. Knight and Schor, in an OECD panel study, report "that economic growth has to some degree decoupled from territorial emissions, but not from consumption-based emissions" (Knight & Schor, 2014, p. 3729). As economies develop, they experience periods of both carbon intensification of GDP and carbon decoupling of GDP. Raupach et al. (2007), analyzing the Kaya model, find evidence of a sharp acceleration in emissions since the early 2000s and note that using the Kaya model breakdown, it appears that energy intensity of GDP and carbon intensity of energy have dramatically risen during that time. This paper's empirical analysis will find supporting evidence of both these phenomena. First, there is global evidence of periods of both decoupling and intensification over time. Second, there is a sharp acceleration in the time series estimates, but the acceleration Raupach et al. (2007) find occurs after a rather sharp decline in the mid-1990s. The results from this paper are similar to those of Raupach et al. (2007), Jorgenson and Clark (2012), and Knight and Schor (2014), suggesting that decoupling is a complicated process, one that is subject to the laws of capitalist accumulation, technical change, and profits, probably not following a stable EKC path.

3.3. Data Sources and Description

In addition to a focus on a time series analysis instead of a panel analysis, this paper utilizes a new CO_2 emissions time series that incorporates some of the effects of the 2008 financial crisis. Global CO_2 data come from Boden, Andres, and Marland (2013) and are an updated version of the CO_2 data used in Steinberger and Roberts (2010). The CO2 time series Boden et al. estimate is global CO_2 emissions from fossil fuel burning, cement manufacturing, and gas flaring: 1751-2010. Since 1751, approximately 365 billion metric tonnes of carbon have been released to the atmosphere from the consumption of fossil fuels and the production of cement. Half these fossil-fuel CO_2 emissions have occurred since the mid-1980s. The 2010 global fossil fuel carbon emissions estimate, 9,167 million metric tons of carbon, represents an all-time high and a 4.9% increase over the 2009 emissions. “The increase marks a quick recovery from the 2008-2009 global financial crisis which had obvious economic and energy use consequences, particularly in North America and Europe” (Boden et al., 2013, website 5/27/2015).

Since 1950, CO2 estimates have come from the UN energy statistics, which is primarily composed of data from an annual questionnaire distributed by the UN. Boden et al. (2013) add gas flaring and cement manufacturing data from the U.S. Department of Energy and the U.S. Department of the Interior’s geological survey.

Burned fossil fuel more accurately captures the human element of CO_2 emissions without the global fluctuations that occur from year to year with parts per million CO_2 (ppm). The Earth's absorption and emission of CO_2 can vary fairly drastically from year to year due to factors out of human control. The Boden et al. (2013) time series captures the anthropogenic contribution much better, even if it is an estimate and not a direct measure of ppm. ppm will have years of large accumulation and periods of relatively small rates of accumulation, which does not necessarily mean that humans are better in one year than in another, just that the Earth did a better job absorbing CO_2 into the natural CO_2 sinks. In addition, seasonal elements need to be taken into consideration when using ppm as a dependent variable in a statistical model. Using ppm requires developing a more elaborate model that takes geological fluctuations into account.

GWP data come from the United Nations main aggregates from *unstats.un.org*. The global aggregated expenditure decomposed GWP time series goes back only to 1970; thus this paper's analysis begins there. All expenditure data are at constant 2005 prices in U.S. dollars, using purchasing power parity for other countries. For the purposes of this paper, we include final consumption expenditures, fixed capital formation expenditure, and export expenditures.[36]

3.4. Methodology Description

3.4.1. Bayesian Linear Regression

Bayesian linear regression is similar to a classical pooled data linear regression (Leamer, 1978). The Bayesian approach differs in that the regression "pools" information

[36] Import expenditures were left out due to the obvious collinearity with exports.

from the data (**X**) and the information not in the data (the prior). The classical pooled method pools information from two or more datasets (**X**) if they were collected in a frequentist manner. The inclusion of information not in the data is one of the dimensions where Bayesian and classical statistics differ. The inclusion of both sets of information (**X** and the prior) allows Bayesians to model full probability, in other words, estimating probability distributions as opposed to only point estimates. This approach is useful when interpreting results since all results from a Bayesian linear regression can be directly interpreted as a probability statement. These full models can also be directly compared to one another using Bayes factors. For instance, estimates from our analysis can be interpreted as the most likely value given the information, and the resulting quantiles are the corresponding values of the probability distribution. These estimates are not in relation to a null hypothesis unless such a hypothesis test is specifically set up. As a result, there will be no need to test for type I and type II errors[37] (unless the analyst desires to test the hypothesis).

As mentioned above, one of the ways Bayesian statistics is different from classical statistics is in its incorporation of information from the data as well as the information outside the data. Properly specifying the nondata information is the primary challenge to the Bayesian analyst. The nondata information needs to be stated completely in a statistical sense, with a full probability distribution. Summarizing nondata information into a probability distribution is difficult. The Bayesian literature has developed many methods for dealing with this inherently subjectively determined

[37] In a sense, the "hypothesis" test is internalized as the prior is "tested" by the data. The posterior probability distribution is tightened for an affirmation of the prior and loosened for a negation of the prior.

probability distribution (Gelman et al., 2014; Greenberg, 2008; Leamer, 1978; Marin & Robert, 2007). The analysis in this paper relies primarily on *Bayesian updating* and theoretical considerations to generate priors.

3.4.2. Bayesian Updating

The first manner in which time will be incorporated into this paper's model is by using Bayesian updating. The Bayesian regression mimics the learning process, as most people know it. Typically, one does not explore a new concept, problem, or dataset in complete ignorance. Instead, individuals bring with them their past relevant experiences, theoretical considerations, and empirical results. Since economics and most social sciences deal almost exclusively in nonexperimental data, all social scientists bring nondata information to their statistical work (Leamer, 1978, 1983). For the Bayesian, this presents the problem of how to specify this external, nondata information in a probability distribution. For the classical statistician, this means engaging in specification searches, treating nonexperimental data as experimental data, ignoring standard error inflation, and modeling specification certainty.[38]

Bayesian updating refers to the learning process described above. As new information becomes available, say in the form of a new dataset, individuals can update their beliefs by combining their data information (the data) with their nondata information (the prior). For the purposes of this paper, previous regression results will be weighted and combined with 'new' data. The information from previous regressions will

[38] Leamer (1978), Leamer (1983), and Kass and Raftery (1995) discuss model and specification uncertainty as well as allude to the problems of frequentist violation of BLUE assumptions. Marin and Roberts (2007), Greenberg (2008), and Gelman et al. (2014) discuss problems arising from frequentist methods and interpretations.

be represented with a probability distribution (the prior) and combined with a ‘new’ dataset to generate a new posterior distribution (a fully expressed conditional probability statement for all the parameters of the model). This new posterior probability distribution is the probabilistic representation of the analyst’s current state of knowledge about the parameters in this paper’s models. When we want to explore a new data series, we will use this posterior probability distribution generated in the past to represent the ‘new’ nondata information (prior) and combine it with the ‘newer’ data to generate a ‘newer’ posterior distribution. This updating is at the core of Bayesian theory and statistical inference and requires no ad hoc assumptions or procedures. In this sense, Bayesian statistics is inherently time-series oriented.

3.5. Empirical Model

3.5.1. Model Design and Reasoning

The model estimated for three priors assumptions is:

$$lnBFFCO_2 \sim lnFCE + lnFKF + lnEX + e. \tag{3.1}$$

All parameters in these models are log-linearized and represent aggregated global expenditure values. The models regressed logged final consumption expenditure (*lnFCE)*, logged fixed capital formation (*lnFKF*), and logged total export expenditures (*lnEX*) on logged CO_2 from burned fossil fuel, cement manufacturing, and gas flaring ($lnBFFCO_2$).

lnFCE includes both global government and global household consumption expenditures. Originally, we attempted to estimate the model with both government and household consumption subsets, but due to limitations in the data (collinearity), we chose the aggregated *lnFCE* over the subsets. *lnFKF* represents global investment. To capture on some level the effects of trade on emission, *lnEX* represents total global expenditures on exports. Imports were left out for obvious collinearity reasons. These models provide a rather poor exploration of the business cycle's impact on emissions due to the use of a 10-year rolling window, which will most likely smooth out smaller economic fluctuations.

One of the very significant limitations of these data is how collinear expenditure data in general are (Figure 3.1). One would expect that global periods that are "good" for consumption would occur at times when it is also "good" to invest. Expenditures are clearly procyclical with respect to one another, as the income of a business is also the consumer's effective demand. When the economy is in a period of strong effective demand, firms, households, and governments are all free to consume more.

This collinearity provides a challenge for analysts interested in seeing the underlying relationships between types of GDP and emissions. The level of correlation between the explanatory variables renders individual parameter estimates more or less meaningless, which produces perplexing individual parameter estimates such as long-running negative estimated values. If an analyst were to take such estimated values seriously, a negative value would mean that global expenditure was driving down emissions! Long-run negative estimated values are clearly a sign of multicollinearity since we know households, firms, and governments are not buying so many trees to completely sink their emissions. It is still, however, beneficial to the models to estimate the individual expenditures since this approach allows for a more refined prior specification. As will be discussed later, prior specification will be subjectively adjusted to deal with some of the issues caused by collinear independent variables.

3.5.2. Collinearity Restrictions

We employ two approaches to address the collinearity of the data. The first is aggregation of variables. Household and government consumption are aggregated to create final consumption expenditure. Aggregation is a method for both classical and Bayesian approaches (Theil, 1971).

The second approach to handling the problems of collinearity of the data is to not accept prior information that is clearly a result of collinearity-induced estimate confusion. As will be discussed in the next section, one variant of the model uses previous regression estimates as prior information in subsequent regressions. For this model variant, prior information about parameters is not accepted if it is negative. Instead, it is replaced by a neutral value (0.5). This value was selected because it is equally far away from absolute decoupling (negative values) and absolute intensification (values greater than one). Parameters with negative estimated values also have the lowest weighting placed on them as well. The weighting of prior information is discussed below.

3.5.3. The Rolling Regression Model

This paper does not use a “formal” time series model; these models are not differenced. Instead, the time series for this model is estimated using a sequential rolling regression. A 10-year sliding window traverses the data year by year, officially beginning with the 1970 to 1979 window and continuing until the final 10-year window, 2001 to 2010. This method is synergistic with a straightforward Bayesian interpretation of the results. The results provide a clear picture of the parameter estimates through time in a manner that accounts for some delay (10 years) in expenditure to emissions. The results also provide a clear picture of model and parameter uncertainty through time, as a full posterior probability distribution is estimated for all 32 periods.

The 10-year window limits the effects of a 1-year deviation in economic or emission activity and allows for a reasonable delay between time of expenditure and emissions. Long-term investments that may have a profound effect on emission may not be fully captured within this time frame, but it seems likely that the emission signatures of most expenditure are at least sufficiently captured.

3.5.4. Defining Priors and Weighting in the Rolling Regression

In this section, the prior and their associated weights are considered. The weights refer to the shape of the prior probability distribution. The smaller the value of the weight, the "flatter" the prior probability, meaning that the actual maximum of that probability distribution (the point given for the prior) is weighted less.

3.5.4.1. Noninformative Prior Nonweighted Model (*reg*)

The first model is used to demonstrate a noninformative prior with a nonadjusting weight, which simulates a non-Bayesian updating rolling regression. No information from the previous period is carried over to the contemporaneous period. For this model, a prior of 0.5 was selected because it is equal distance away from absolute decoupling (values <0) and absolute intensification (values >1). The value of 0.5 was selected for each iteration of the regression for the whole time series. Because the prior value is set for each iteration of the rolling regression, this model does not have fluctuating weighting functions. The weighting value for the prior is set to 0.001; this is a flat prior, meaning not much emphasis is placed on the prior of 0.5 in relation to the data maximum likelihood estimator.

The regression estimated, however, is still considered "Bayesian" since it produces a fully defined probability model. There is no external information incorporated in the prior and a rigid treatment of the 0.5 priors. This model should still outperform an OLS estimate since it does contain more information, but the model can be considered to be a proxy for such frequentist methods.

3.5.4.2. Decoupling Model Prior (*regdc*)

The second model considered in this paper's analysis uses its prior to simulate steady decoupling. For this model, initially, a prior of .75 is selected. The value of .75 represents a "good" guess based on the summed model value for the 1970-1978-regression window,[39] which also agrees with the nonmodel intuition: increasing expenditure will increase pollution but probably not in a one-to-one manner. For each iteration of the rolling regression, this model's prior decreases by 0.01, reflecting

[39] The model was 'calibrated' by progressively building up the rolling 10-year window starting from the 1970-1974 data window. An additional year was added to the window, expanding the regressions data frame to 1970-1975 and so on until the window 1970-1979 was reached. During the 'calibration' phase, weights were not adjusted, but Bayesian updating was used to generate priors.

technological change and steady decoupling. The rate of decrease represents not more than a guess and is not based on estimation or firmly held prior beliefs. The prior decreases from .75 to .44 through the course of the time series.

This model receives a weighting treatment different from that for the noninformative, nonweighted prior model previously discussed. This model is not trying to be a proxy for a frequentist method but rather in a Bayesian manner test the hypothesis of consistent decoupling. Thus, the weighting function adjusts according to how well the prior did for each parameter being estimated. If a parameter value, *lnFCE* for instance, were estimated to be negative, the weight on the subsequent iterations prior for *lnFCE* would be ‘flat’ or weighted at 0.001. Using the posterior probability distribution, the weighting function assesses whether the probability distribution shows sign agreement for the parameter estimates at two separate levels (2.5-97.5% and 25-75%). If a given parameter posterior probability distribution has sign agreement at the 25 to 75% probability levels, then the subsequent prior will have increased weight placed on it going from 0.001 to 0.01. If the same parameter posterior probability distribution has sign agreement at the 2.5-97.5% probability levels of the posterior, then the prior weight on the subsequent iteration will be raised further from 0.01 to 0.1. A robust parameter estimate is demonstrated by sign agreement at the 2.5-97.5% probability levels. However, due to the limitation of the data (collinearity), these adjustment weights and ‘robust’ parameter estimates are used only for weighting and later on in updating and are not explored in isolation.

3.5.4.3. Bayesian Updating Prior Model (*regrw*)

For the last model, the analysis fully implements a Bayesian updating framework with adjusting weights. As discussed earlier (Section 3.4.2), Bayesian updating within this rolling regression model uses the previous iteration posterior probability for each estimated parameter as the priors for the next iteration's regression. This approach leads to information from previous periods, say data from the 1970s, being incorporated into the regression for the 2000s. For each parameter within these models (the *intercept, lnFCE, lnFKF,* and *lnEX*),[40] the previous period's posterior becomes the next period's prior except in the case when a negative value is estimated in the previous period. If, for instance, *lnEX* had been estimated with a negative value, the prior would not take the clearly incorrect negative value but instead assign *lnEX* in the next period a prior value of 0.5 with a weight of 0.001.[41] Negative values on the posterior parameter ranges of 2.5-97.5% and 25-75% are handled in the same manner as the regression model that was emulating steady decoupling (*regdc*) for prior weighting purposes. This approach incorporates information from previous regressions in the most explicit manner, allowing for longer run trends (beyond the 10-year window) to be accounted for on some level.

3.5.5. Bayes Factors

The Bayes factor is a Bayesian tool that "corresponds to the classical odds or likelihood ratio the difference being that the parameters are integrated rather than

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[40] The *intercept* value does not have any weighting or adjustment. It is included only to generate a proper prior distribution.

[41] Since it is extremely unlikely that any aggregated expenditure category has experienced absolute decoupling, negative values are thrown out in the updating process as they are viewed to be the result of multicollinearity.

maximized under each model" (Marin & Robert, 2007, p. 29).[42] The Bayes factor allows for hypothesis testing in a fully Bayesian manner where an analyst can directly compare model posterior probabilities to one another and get a relative sense of which model the data 'prefer'. For the purpose of this paper's analysis, Bayes factors are employed to determine what prior the data prefer and if there is positive support in favor of one model specification over another.

The results of the Bayes factors presented in this paper are the logged likelihood ratios of one model over another. According to Kass and Raftery, values between 0-2 demonstrate evidence "Not worth more than a bare mention supporting one model to another model" (1995, p. 777). Values 2-6 represent "positive" evidence supporting one model over another, 6-10 represent "strong" support, and values greater than 10 represent "very strong" support.

Both the *regrw* and *regdc* outperform the *reg* model. Figure 3.2 presents the results for both *regdc* and *regrw* in relation to the *reg* model. There are only 3 years where the *reg* model performs as well as *regdc* (2006, 2007, and 2008) and 4 years where *reg* performs as well as *regrw* (2005, 2006, 2007, and 2008). Figure 3.2 suggests a dynamic prior for the most part outperforms a noninformative prior; Bayesian updating produces a better model.

For *regrw* and *regdc*, both models seem to have similar posterior marginal likelihoods (results shown in Figure 3.3). *regrw* outperforms *regdc* enough to mention for 3 years (1999, 2000, and 2001) whereas *regdc* outperforms *regrw* for 3 years (1979, 1985, and 2005). These two models are nearly identical with the exception of a few years

[42] Bayes factors were developed in Kass and Raftery (1995).

while one model adapts to a new time series relationship. With the exception of 1979, all differences between these two models are associated with large movements in the data that will be validated by all three models. In the next section, it will be shown that although there are differences in the posterior marginal likelihood of these three models, all three find the same relationship within the data.

3.6. Model Results

Figure 3.4 presents the results for the three models. The models *reg* and *regdc* produce almost identical results. The reason *regdc* has a higher posterior marginal likelihood, and thus a higher Bayes factor, is because of small differences in the variances, posterior distribution, and low weighting values of the prior for *regdc* for most of the time series.[43] The most obvious result from these three models is the sharp decline in the estimated carbon intensity of GWP in the 1990s. Throughout the 1980s, emission intensity appears to fluctuate between 0.6 and 0.8, meaning for every 1% increase in GWP there is a 0.6-0.8% increase in CO_2 emissions. After 1992, there is a significant and profound decline in CO_2 intensity of GWP, bottoming out in 2000 (reflecting the whole decade of the 90s). The data are not rich enough to test or discern why all three models estimate a rather significant decoupling during the 1990s. However, one could reasonably expect two potential explanations for this decoupling: The collapse of the Soviet Union's notoriously carbon-intensive economic system and the strong growth in GWP in the mid-1990s. As the global production became cleaner with the fall of the Soviet economies, the CO_2 time series flattened out while the GWP surged, which either produced a couple of

[43] By not achieving high prior weights, the *regdc* model ends up differing from the data nearly as much as the *reg* model does.

years of serious decoupling or at least the appearance of serious decoupling before the growth in GWP, and later China again strongly pulled CO_2 intensity up.

Following this dramatic decline is a corresponding intensification that leaves the carbon intensity of GWP roughly at its pre-decline levels (>1992 levels). This intensification in the early 2000s was also captured in the Kaya model discussed earlier (Raupach et al., 2007).

The three models clearly show supporting evidence of Jorgensen and Clark's dynamic decoupling behavior of 'mini-cycles' but on a global scale (also seen in Knight & Schor, 2014). Even prior to the sharp cycle in the 1990s, which is most likely historically specific, the 1980s presented fluctuation and a 'stable' but 'unclear' behavior.

There is clearly a need for additional work, especially for more time series work that can control for dramatic changes in global production, such as the collapse of the Soviet Bloc in the early 1990s, as some panel studies do. It is reasonable to speculate that changing global production as a result of the decline of the Soviet Union and the rise of information technology resulted in a temporary decoupling of global production from emissions. It is also reasonable to speculate as Raupach et al. (2007) do that the rise of China and India has driven the troubling intensification through the 2000s.

For *regrw,* we see *regrw* estimates a lower value or more decoupling in the late 1990s and early 2000s. For the three regressions that the *regrw* model clearly outperformed both *reg* and *regdc* models (1999, 2000, and 2001), *regrw* is estimating absolute decoupling. However, the return to 'normal' values in the 2000s was also a sharp recovery. The *regrw* prior would have more easily incorporated the structural break caused by the Soviet Bloc's collapse and other changes in production and consumption in the 1990s. The *regdc* model, as its prior values were predetermined to follow a steady decline, would have resisted the model being pulled down as far as *regrw*. Correspondingly, in the years of intensification, *regrw* would have still been using priors formed during the decoupling period and thus would have had to adjust to the intensification over several iterations of the model. *regdc* would have had a higher prior for the period of recovery and would not have been incorporating the past information into its estimations. This inertia might explain some of the differences between the models following the 90s.

The most interesting result from these three models is the similarity of the estimates, which show that the data very strongly exhibit the characteristics displayed in Figure 3.4. The decoupling and intensification that was estimated in the time series for these three models is not the result of biased priors or an extensive specification search; rather it appears to be an inherent characteristic of these data. There appears to be decoupling/intensification mini-cycles on an aggregated and global scale, not just for individual countries. All three specifications point to global mini-cycles, a 1990s decoupling and an intensification in the 2000s as well as fluctuation in the 1980s.

The posterior probability distribution for all three models shows a similar result. Figure 3.5 displays the points at the 25, 50, and 75% marks for all three models. Again, *reg* and *regdc* end up with nearly identical estimations as the evidence drowns their priors out while *regrw* mirrors very closely the results of the other two models. One clear result from Figure 3.5 is an asymmetry in model certainty with regard to the decoupling in the 1990s and the intensification in the 2000s. The models appear to be more certain about the decoupling in the 1990s since the distance between the 25-75% estimates does not change that much. In contrast, the 2000s intensification leads to greater model uncertainty among all the models as the 25-75% estimates grow further apart, suggesting a flattening posterior probability distribution. Figure 3.5 also demonstrates the level of uncertainty that exists within this dataset and decoupling studies in general. For instance, in the early 2000s, the models are equally sure that the true model estimate is nearly -1.5 or 3! Although this is the most uncertain the models were throughout the time series, it speaks to the fact that all decoupling studies should be taken with a grain of salt, as there exist many potential model specifications that could generate 'significance'. This paper's analysis attempts to deal with some of the specification uncertainty by estimating three models that utilize different prior information. Surprisingly, the data seem to indicate that there is an underlying trend throughout this time series even if the trend is fuzzy.

3.7. Conclusion and Continuations

This paper's analysis has lent supporting evidence to other empirical works that show a dynamic relationship between GWP and CO_2 emissions (Jorgenson & Clark, 2012; Knight & Schor, 2014; Raupach et al., 2007). All three models show evidence of mini-cycles and large movements within the decoupling relationship. These dynamics are critical for understanding how much 'greening' of growth should be accounted for in economy models and other forecasts.

One of the areas this study highlights for future research is the level of model uncertainty involved with linear regressions of these data. Many different models that potentially arrive at very different conclusions could be fitted to the data. There might be years where significant statistics could be found, but an analysis of the entire time series demonstrates that any such results should be treated with skepticism.

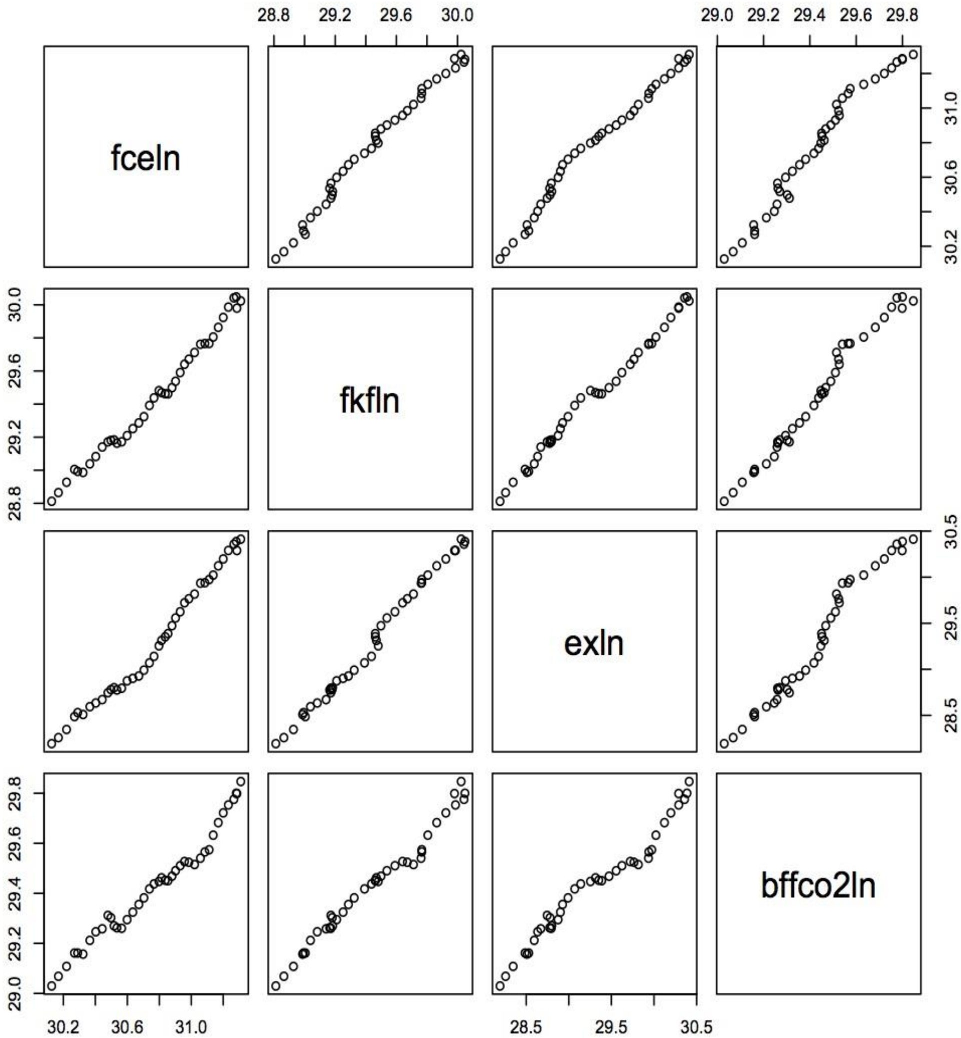

*Figure 3.1***.** Correlation plot.

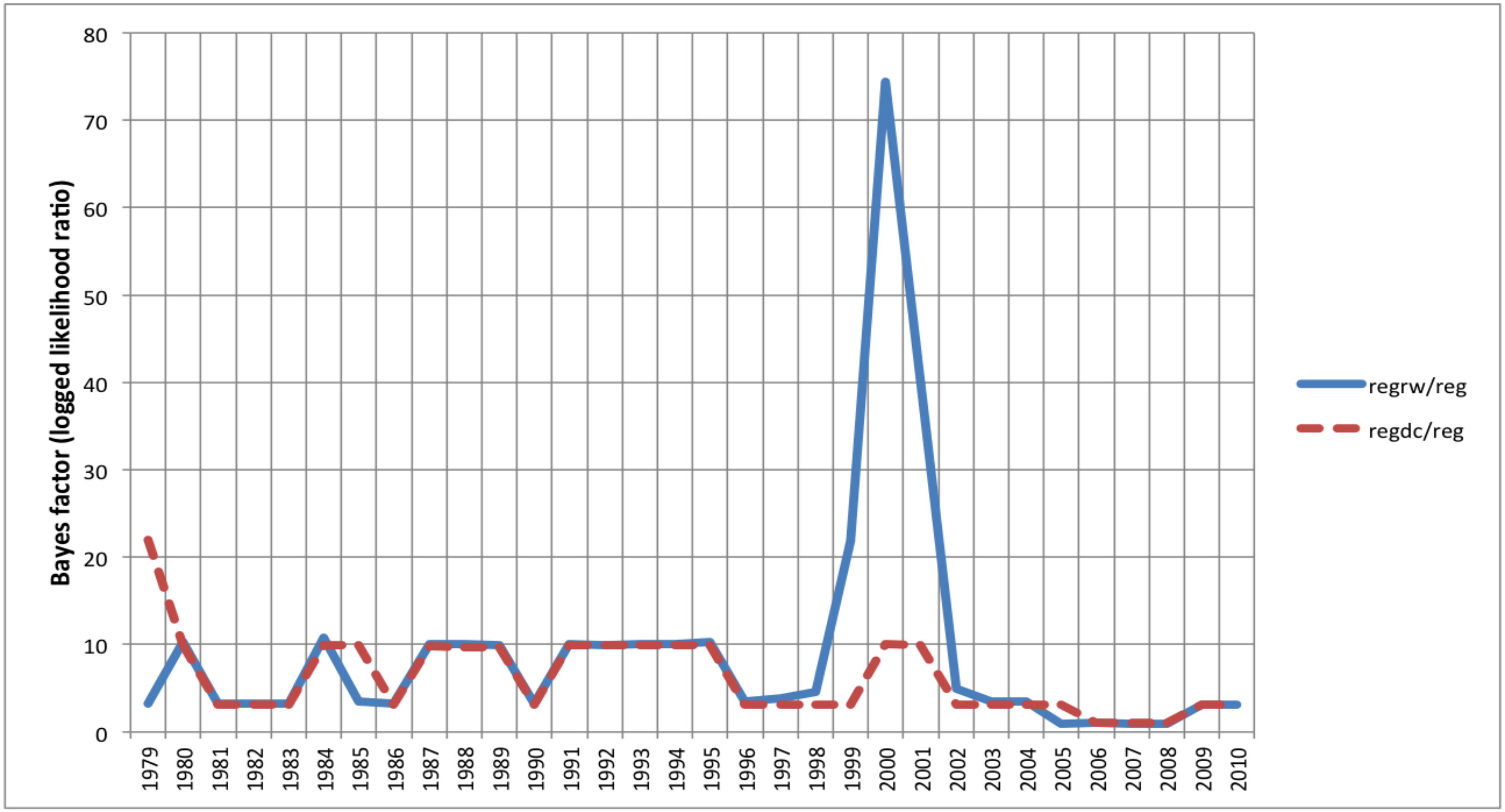

Figure 3.2. Bayes factor comparison for both *regrw* and *regdc* to *reg*.

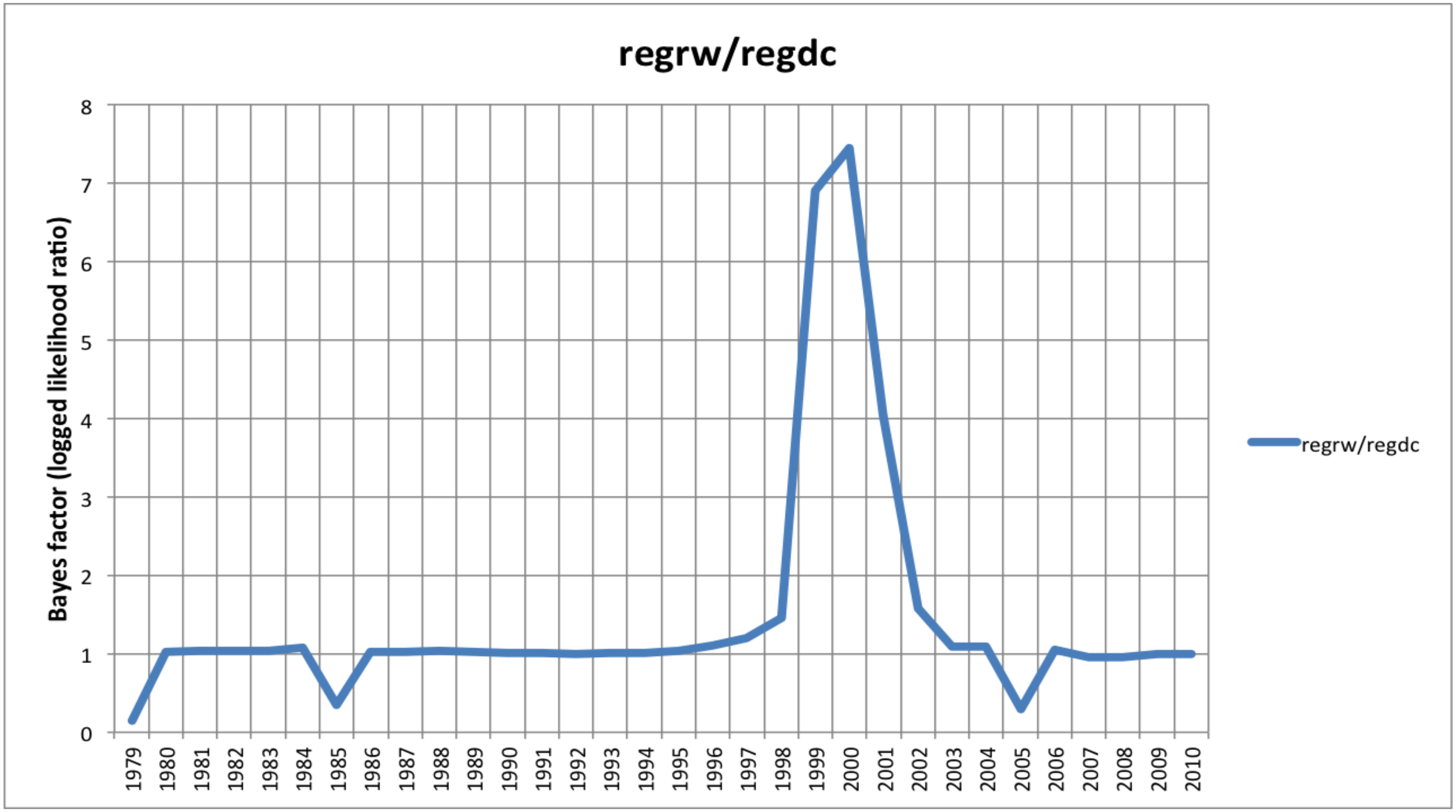

Figure 3.3. Bayes factor comparison for *regrw* to *regdc*.

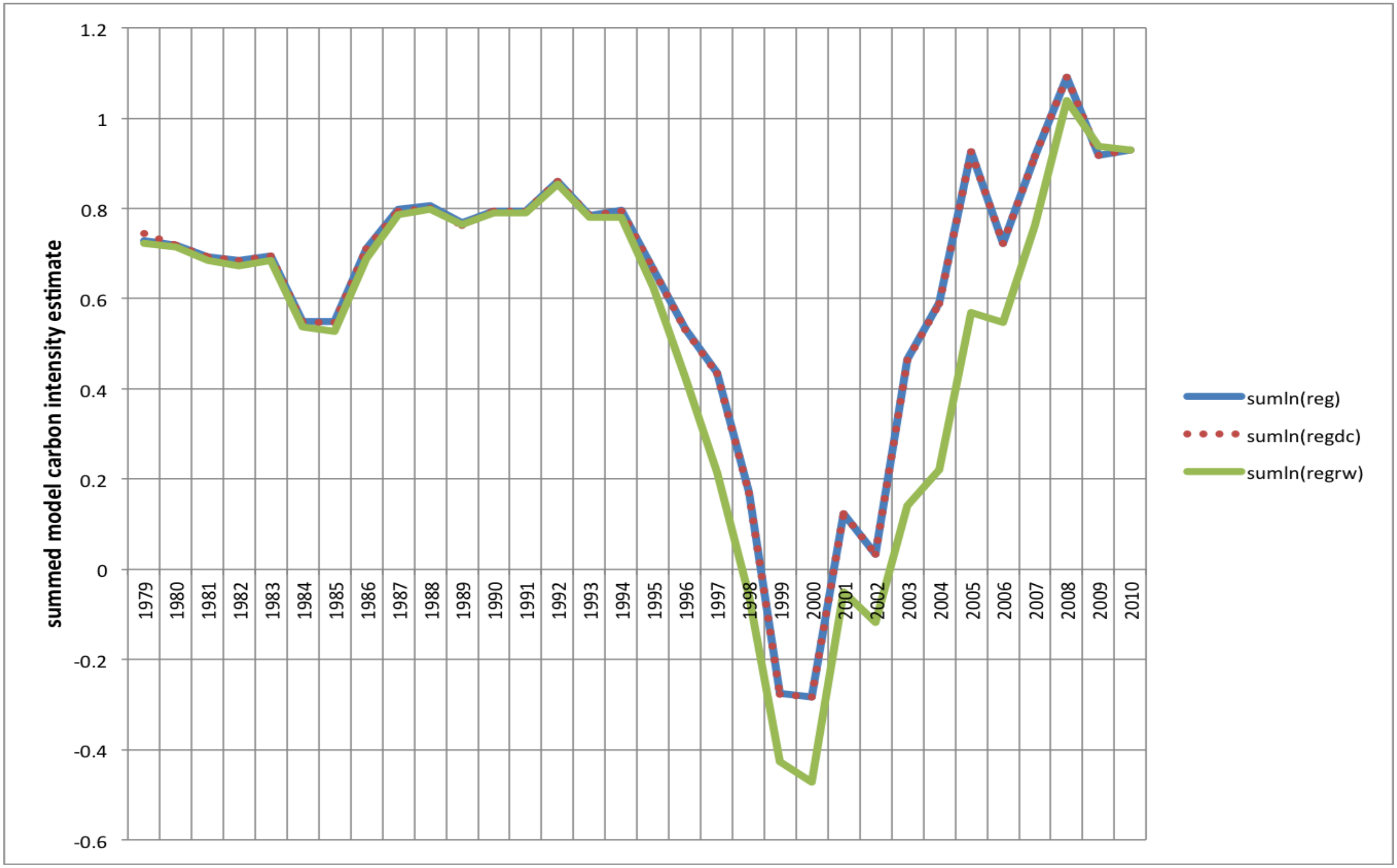

Figure 3.4. Summed results for *reg*, *regdc*, and *regrw* models.

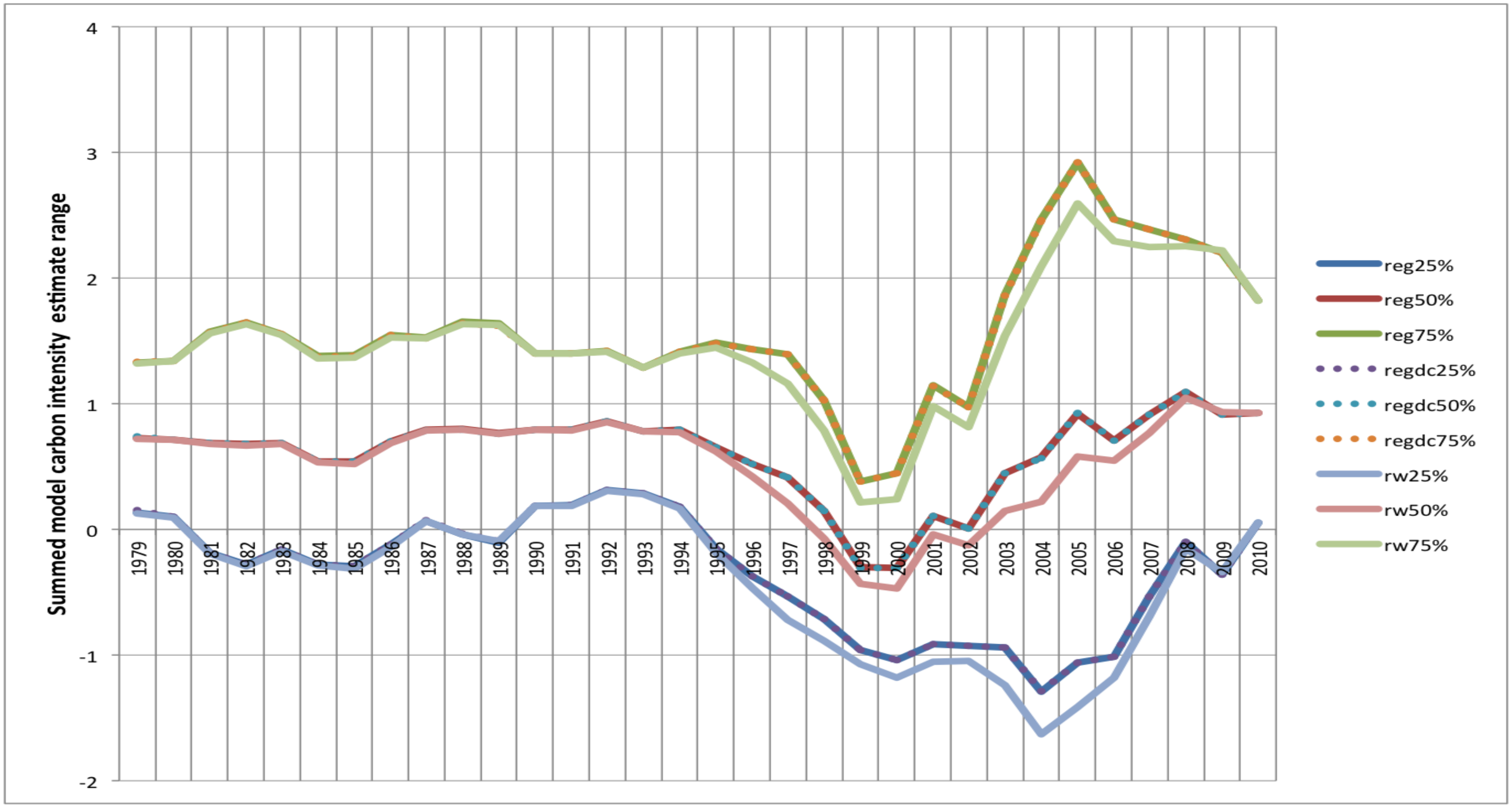

Figure 3.5. 25%, 50%, and 75% quantiles for *reg*, *regdc*, and *regrw* models.

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